1A

N. M. NEWMARK

L ENGINEERING STUDIES

STRUCTURAL RESEARCH SERIES NO. 68

1

STATIC TENSILE TESTS OF LARGE I-SECTION CONNECTIONS

trailer card → RIVETED + BOLTED STRUCTURAL JOINTS 00 PROG. REPT. JAN 54
PROJ. 4

By

J. R. FULLER

T. F. LEAHEY

~~and~~

W. H. MUNSE

Jan 54

UNIVERSITY OF ILLINOIS
URBANA, ILLINOIS

STATIC TENSILE TESTS
OF LARGE I-SECTION CONNECTIONS

by

J. R. Fuller
T. F. Leahey

and

W. H. Munse

A Progress Report of an Investigation

Conducted by

THE UNIVERSITY OF ILLINOIS ENGINEERING EXPERIMENT STATION

in Cooperation with

THE RESEARCH COUNCIL ON RIVETED AND BOLTED STRUCTURAL JOINTS

THE ILLINOIS DIVISION OF HIGHWAYS

and

THE BUREAU OF PUBLIC ROADS

Project IV

Urbana, Illinois

January 1954

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Cont'd)

SYNOPSIS

The test data reported herein deals with the fundamental behavior of several large structural truss-type connections consisting of 1/2-in. gusset plates and 18-in. I-beams, fabricated with either rivets or high strength steel bolts.

Of the three specimens tested, one was fastened with hot-driven rivets while the other two were bolted. One of the bolted specimens was assembled with hardened beveled washers against the sloping faces of the I-beam flanges to provide parallel bearing faces for the bolts; the other was fastened using only hardened flat washers.

A study of the load-slip and load-strain behavior is made for the three specimens and fundamental differences in their behaviors are pointed out. The distribution of stresses across the critical sections in the webs of the members is analyzed for all stages of the tests to determine what portion of the load on each specimen was resisted by the web. This makes it possible to determine the efficiency of the web and the flanges in resisting the loads applied to the members.

I. INTRODUCTION

1. Object and Scope of Investigation

The tests reported herein were designed to study the fundamental behavior of several large structural truss-type connections fabricated with rivets or high strength bolts. Very little information is available concerning the interaction of the various parts of such members and connections when loaded to failure in tension. Consequently, this study was planned to determine the manner in which the load is distributed to the gusset plates as well as to study the effect of the type of fastener upon the behavior of the member and the connections.

With the advent of the high strength steel bolt as a means of fabricating steel structures, a number of new problems arose. The bolt holes are made 1/16-in. larger than the nominal size of the bolts. Therefore, the manner in which the load is transmitted through a long connection containing high strength bolts may differ considerably from that found in similar riveted joints wherein the rivets fill the holes. Questions have also been raised concerning the possibility of an unbuttoning or early initiation of bolt failure in a long connection. Another of the problems concerns the need for beveled washers in bolted connections of standard I-sections--a saving in fabrication cost would be realized if the beveled washer could be eliminated. These are a few of the principal questions studied in the tests discussed in this report.

Three specimens were tested in this study; each consisted of an 18-in. 54.7-lb I-section connected to 1/2-in. gusset plates with either 7/8-in. rivets or 7/8-in. high strength bolts. One specimen was fabricated with hot-driven rivets--the other two with high strength steel bolts and hardened washers*. One of the bolted specimens was assembled with flat hardened washers under both the head of the bolt and the nut. The second bolted specimen was assembled with a hardened beveled washer between the head of each bolt and the sloping flange of the I-section, and a flat hardened washer under the nut. The beveled washers had a slope of 16 2/3 percent to provide parallel bearing surfaces between the head of the bolt and the nut.

The principal factors studied in these tests were: (1) the slip or deformation of the joints under load and the effect of this slip on the strain distribution throughout the members, (2) the effect of the type of fastener on the behavior of the members, and (3) the distribution of load in the various parts of the members.

2. Acknowledgements

The tests described in this report are a part of an investigation being carried on as a result of a cooperative agreement between the Engineering Experiment Station of the University of Illinois, the Illinois Division of Highways, the Bureau of Public Roads, and the Research Council on Riveted and Bolted Structural Joints. This investigation is a part of the structural research program of the Department of Civil Engineering under the general direction of N. M. Newmark, Research Professor of Structural Engineering and was carried out by J. R. Fuller and T. F. Leahey, Research Assistants in Civil Engineering, working

---

* The bolts were ASTM Designation: A325, "Quenched and Tempered Steel Bolts and Studs with Suitable Nuts and Plain Washers".

under the direct supervision of W. H. Munse, Research Associate Professor of Civil Engineering. R. C. Bergendoff, former Research Assistant, and W. S. Beam, Research Assistant, assisted in testing; E. Chesson, Research Assistant, has assisted in the preparation of the report.

The tests described in this report were approved by the Project IV Committee of the Research Council on Riveted and Bolted Structural Joints. The members of the Project IV Committee are as follows:

II. DESCRIPTION OF SPECIMENS AND TESTS

3. General Description

The specimens were tested in a 3,000,000 lb Southwark-Emery hydraulic testing machine in Talbot Laboratory at the University of Illinois. One of the specimens with all of the instrumentation attached and ready for testing is shown in Fig. 1.

The specimens were fabricated from an 18-in. 54.7-lb I-section and 1/2-in. gusset plates as shown in Fig. 2. The dimensions of the members and the spacing of the fasteners were the same for all three specimens. In addition, the I-section material was cut from one length of beam in an effort to obtain relatively uniform mechanical properties for all of the members. Consequently, the only difference between the three specimens was the type of fastener.

The fasteners for both joints of each specimen were arranged in four longitudinal lines*: two lines 3 1/2-in. apart in each flange. There were seven fasteners in each line at a pitch of 2 5/8 in. or a total of 28 fasteners in each joint of a specimen. All holes were 15/16-in. diameter and were drilled with the gusset plates and I-sections clamped together to insure accurate matching during assembly.

Specimens S-1 and S-2 were fabricated with high strength steel bolts. Specimen S-1 was assembled with hardened beveled washers between the heads of the bolts and the sloping faces of the I-beam flanges. This arrangement provided parallel bearing faces for each bolt. Only hardened flat washers were used for Specimen S-2. Thus as the bolts of Specimen S-2 were torqued, the bolt shanks were bent through an angle of approximately ten degrees as the bolt heads were pulled into contact with the sloping faces of the I-beam flanges.

* A line of fasteners is referred to herein as a series of fasteners parallel to the direction of loading, and a row as those fasteners which lie on a line normal to the direction of loading.

All of the bolts in Specimens S-1 and S-2 were torqued in accordance with the Research Council on Riveted and Bolted Structural Joints Specification for "The Assembly of Structural Joints Using High Tensile Steel Bolts". This specification provides for a minimum tension of 32,400 lb for the 7/8-in. high strength steel bolts.

The connections of Specimen S-3 were fabricated by a large structural steel fabricator with machine-driven rivets specified as ASTM Designation: A 141. Project personnel were present during the riveting operation to witness and inspect the driving. Prior to the final assembly of the specimens, all contact surfaces were cleaned and wire-brushed to remove loose mill-scale, burrs and rust.

4. Mechanical Properties of I-Section Material

The average mechanical properties of the I-section material as determined by laboratory tests of standard flat coupon specimens are given in Table 1. These properties, in general, met the requirements of ASTM Designation: A 7 for "Steel for Bridges and Buildings".

The variation in the ultimate strength, the percent elongation in eight inches, and the yield point of the I-section is shown in Fig. 3. It may be noticed that the yield strength and ultimate strength were lowest at the web-flange junction. The toes of the flanges and the center portion of the web evidently received more extensive cold-working in the rolling process than did the areas at the junction of the web and flanges. Consequently, the highest yield was obtained in coupons taken from the central portions of the web and the toes of the flanges.

The chemical composition of the I-section material as determined by mill analysis is given in Table 2.

5. Bolt Calibrations

The load-elongation and load-torque relationships for the bolts of Specimens S-1 and S-2 were determined with a "bolt-calibrator" developed in the Structural Research Laboratory at the University of Illinois. This calibrator is extremely sensitive and can be adjusted for various bolt sizes and grips. As a bolt is torqued in the calibrator, the bolt tension transmitted to the bolt shank can be measured.

The average load-elongation relationship for the Specimen S-1 bolts (parallel bearing surfaces) is shown in Fig. 4(a). This calibration curve was obtained by tightening the bolts in the same manner as they were torqued in the test specimen. It may be noted that the yield strength of the bolts at an offset of 0.0005 in. was 36,000 lb. This is the elastic proof load specified in ASTM Designation: A325 for 7/8-in. bolts loaded axially. Load-torque relationships were also determined (see Fig. 4b) for the bolts which were used without the beveled washers (bearing surfaces not parallel). An attempt was made to correlate the load in these bolts with the elongation of bolts with plain washers but, because of the bending in the bolt shanks during the tensioning and the shifting of the bolts in the holes as the heads pulled into full bearing, the values were not consistent. The slope of the average load-torque relationship may be noted as 81.0 lb/ft lb.

6. Instrumentation and Equipment

Twenty-six SR-4 (type A-11, 1-in. gage length) wire-resistance strain gages were applied to each specimen. Eight of the gages were located around the I-section at the center of each specimen to indicate the uniformity with which the strain was distributed across the section.

The remaining 18 gages were placed on both sides of the web at one end of the specimen and in line with the first, third, fifth, and seventh transverse rows of fasteners. It was intended that these gages indicate the manner in which the strains were distributed across the web during the early stages of the test and to indicate how the strains were redistributed when slip occurred in the specimens. Thirteen of these latter gages were placed on one face of the web and the remaining five were placed on the other face at selected positions opposite five of the other gages. The positions and the reference numbers of all of the strain gages are shown in Fig. 5.

Slip dials were attached to the gusset plates at selected positions as shown in Fig. 5. Small lugs were soldered to the I-sections such that the slip dials were in contact with the lugs at the center lines through the various rows of fasteners. Any differential movement between the gusset plates and the I-sections at these fasteners was indicated by the dials. Two of these dials can be seen in Fig. 6.

Brackets were attached to the gusset plates at the outer rows of fasteners of each connection to obtain the total extension of each specimen. These measurements included the total slip in the connection at each end of the specimen as well as the elongation in the I-section between the connections.

One end of each specimen, up to within approximately 2-in. of the center section, was covered with brittle coatings approximately 24 hours before testing began. For Specimens S-1 and S-3, a brittle lacquer* was used on one half of the section and whitewash was used on

* Brittle lacquer employed in this investigation was "Stresscoat".

the other half: for Specimen S-2, only whitewash was used. These brittle coatings were employed to survey the distribution of the strain in the joints, to locate points of high stress concentrations and to detect differences in the behavior between the riveted and bolted specimens.

7. Description of Tests

An average of about 15 load increments were taken in the tests of each of the three specimens. The strain gages and slip dials were read immediately after each loading increment. In addition, the brittle coatings were surveyed both during the loading and recording periods, and the crack patterns were outlined as changes were noticed.

All strain gages and slip dials were read immediately after each major slip in the bolted specimens. As would be expected, the load always decreased after a large slip. After the readings were completed at this lower load, the load was increased to its preslip value and another set of readings was taken. When the load reached a maximum the slip dials were removed to protect them from damage when the member failed. Thus a relatively complete record was obtained of the load-slip behavior and of the strain distribution in the connections.

III. RESULTS OF TESTS

8. General Discussion of Tests

One of the connections of Specimen S-1 (with beveled washers) experienced the first major slip at a load of 364,000 lb. When this slip occurred, the load dropped to 300,000 lb. The load was then increased to 368,000 lb and the second joint slipped causing the load to drop to 302,000 lb.

At a load of 468,000 lb on Specimen S-1, cracks appeared in the Stresscoat on the gusset plate indicating that local yielding was taking place. However, general yielding of the gusset plates did not occur until a load of approximately 640,000 lb was reached. Lüders' lines (diagonal shear lines) appeared in the central portion of the web at the center of the specimen at a load of 645,000 lb. These lines on the web of Specimen S-1 are visible in Fig. 6.

The maximum load resisted by Specimen S-1 was 798,000 lb. The fracture of this specimen is shown in Fig. 7. It may be noted that the fracture occurred at the first row of fasteners. The toes of the flanges, at the fracture section, showed considerable necking-down but the remainder of the fracture did not. The fasteners at this fracture section were bent, but still intact.

One of the connections of Specimen S-2 (plain hardened washers) exhibited first major slip at a load of 368,000 lb, only 4,000 lb higher than the load at first major slip in Specimen S-1. At a load of 450,000 lb, part of this same joint slipped again; the second joint of this specimen did not slip until a load of 520,000 lb was reached but at this load the entire joint slipped into bearing.

Lüders' lines began to form in the web at the center of the specimen at about 550,000 lb. These were of the same general nature as those which appeared in Specimen S-1 as shown in Fig. 6. The maximum load resisted by

Specimen S-2 was 808,000 lb, and failure occurred through the critical net section in the top joint as shown in Fig. 8.

There was no sudden slip in the riveted connections, Specimen S-3. However, the load-slip relations for the specimen indicate that the rate of slip increased gradually with the higher loads. The whitewash began to spall-off the first row rivet heads at approximately 150,000 lb and the brittle lacquer on the toes of the I-section at the first row of rivets started to crack at about 240,000 lb. At this latter load, lacquer cracks were noted also on the lower gusset plate just below the last row of fasteners. When the load reached 760,000 lb the rivets in one gusset failed suddenly in shear. This failure is shown in Fig. 9(a).

After the initial shear failure, all of the rivets in the connection were removed, and the joint was re-assembled with high strength steel bolts and beveled washers. These bolts were installed at the bolt tension designated in the specification for the "Assembly of Structural Joints Using High Tensile Steel Bolts".

After the connection had been bolted, the specimen was again loaded to failure; the second riveted connection failed in shear after a maximum load of 818,000 lb had been reached. This second shear failure is shown in Fig. 9(b). The average shearing stress on the rivets at the time of the first and second failures was 45,000 and 48,600 psi respectively.

The second connection was then bolted with high strength steel bolts and beveled washers, in the same manner as the first joint, and a third attempt was made to obtain a tension failure. The maximum load sustained by Specimen S-3 in this third testing was 870,000 lb. The final fracture of the Specimen S-3 section is shown in Fig. 10.

The fracture of Specimen S-3 passed through the first row of holes in one flange and between the first and second rows of holes at one of the bolts in the second flange. One of the bolts in this latter flange failed in shear prior to failure of the member. This probably occurred at the same time that the toe of the flange at the fastener fractured (see Fig. 10). Of course, the specimen had been loaded to 760,000 lb before the bolts in this joint were installed and therefore this joint could hardly be considered normal. It does, however, raise the question as to whether high overloads on bolted joints affect the behavior or strength of such a joint.

9. Load-Slip Relationships

(a) Specimen S-1:

Figure 11 shows the load-slip relationships for the eight slip dials at the first rows of fasteners of Specimen S-1 (beveled washers). Whenever major slip occurred, the load would drop. It can be assumed that the load would begin to drop at the same instance that the slip started, but it was not possible to record load and slip during the slipping of the joints. Therefore, the exact shape of the load-slip relationship during slip is not known. For purposes of this report, slip is indicated on the diagrams as a straight dashed line, from the previous increment to a point at the maximum slip and the load at which this slip occurred. Thus a large major slip is shown as a long, nearly horizontal dashed line. If the slip occurred at another section, the drop in load shows up as a downward pip with little increase in slip.

Plastic deformation of the material around the fastener holes will have an effect on the load-slip curves also. The brittle lacquer studies indicated that the toes of the flanges at the first row of fasteners began to yield at about 240,000 lb. Therefore the load-slip curves may be expected to show, at this load, an increase in the rate of slip. The load-slip curves do begin to bend over at approximately this load and continue to do so until they are interrupted by sudden slip.

From the load-slip curves of Fig. 11, it can be seen that the first major slip in one connection occurred at 364,000 lb. The second joint of Specimen S-1 slipped at a load of 368,000 lb. Thus, a load of 366,000 lb may be taken as the average load at first major slip for this specimen. This corresponds to an average nominal shearing stress of 21,700 psi and an apparent coefficient of friction of 0.40.

Figure 12 shows the load-slip curves for the slip dials in a line on Specimen S-1. <u>All</u> of these dials showed first slip at 364,000 lb. This indicates that the entire joint slipped at this same load; slip did not progress gradually along the joint. The slip curves for this specimen indicate also that large slips occurred only once or at the most twice before the fasteners were in bearing. After the fasteners are in bearing the load-slip relation increases gradually to general yielding and then to failure.

(b) Specimen S-2:

The load-slip curves for slip at the first row of fasteners of Specimen S-2 (plain washers) are shown in Fig. 13. First major slip occurred in the lower joint of this specimen at a load of 368,000 lb but did not occur in the upper joint until the load had reached 520,000 lb. The loads for first major slip correspond to nominal shearing stresses of 21,800 and 30,900 psi respectively; the corresponding apparent coefficients of friction are 0.41 and 0.57.

The load-slip curves for Specimen S-2 were, at times, somewhat erratic (see curves C and E on Fig. 13.) and did not always show clearly when the fasteners went into bearing. This may have resulted from the bending in the bolt shanks which resulted when the bolts were torqued into position, or possibly other factors. The joints seemed also to rotate somewhat at the higher loads, slipping a small amount on one side and then the other. However, the first major slip occurred at once along all lines of fasteners in each connection. The load-slip curves for the Specimen S-2 fasteners are shown in Fig. 14, and, as for Specimen S-1, indicate that the entire connection slipped as a whole.

(c) Specimen S-3:

Load-slip curves for Specimen S-3 (riveted) are shown in Fig. 15 and are believed to be typical for riveted joints. The specimen seemed to slip as a unit in the same manner as the bolted joints. This is evident in the lower portion of Fig. 15 where the load-slip curves for a number of rivets in a line are seen to be almost identical.

An average load-slip curve for the first row slip dials of each specimen is presented in Fig. 16. These curves show the relative load-slip behavior of the three types of joints tested. The slip, up to a load of approximately 300,000 lb (17,800 psi shear and 22,500 psi tension on the net section) was greater in the riveted joints than in the bolted joints, but beyond this point the slip in the bolted joints, for a given load, was greater than the slip in the riveted joint. However, at the highest loads the slip in the three joints again did not differ greatly.

At failure, the slip between the ends of a gusset plate of Specimen S-2 and a transverse line on the flange was found to be nearly 3/8 in. (see Fig. 17). This gives an excellent indication of the large amount of deformation the connections withstood before failure.

The overall load-slip data for each of the specimens is summarized in Fig. 18. It may be noted that these are somewhat similar to the load-slip curves obtained for the individual connections. The principal difference is in the relative effect of the major slip on the load-slip relationship because of the inclusion of the deformation of the I-section and the gusset plates in the overall-slip, the relative effect of the major slip at the connections is reduced. For the tests of Specimens S-1, S-2 and S-3, the total overall-elongation at a load of 550,000 lb (after all of the joints had slipped) was approximately 0.32, 0.34 and 0.21 in., respectively. If the members had been 30 ft long between the last rows of fasteners instead of 5 ft, the elongation of the added section between the gusset plates would have been approximately 0.35 in., for the same load, and the overall elongations approximately 0.67, 0.69 and 0.56 in. for the three corresponding members. Thus, in members five times the length of the test specimens, the total overall extensions under a load of 550,000 lb would all have been more nearly the same.

The lower part of Fig. 18 shows, to a larger scale, the initial portions of the average overall load-slip curves for each specimen. The average curve for Specimen S-1 is linear up to 200,000 lb. During the remaining load increments, local yielding in the toes of the flanges began to affect the rate of deformation.

10. Load-Strain Relationships

Figures 19(a) and 19(b) present the load-strain relationships obtained with SR-4 gages on Specimen S-1 (beveled washers). The locations of these gages are shown in Fig. 5 and in the small diagrams on Fig. 19.

The load-strain curves indicate that major slip in the joint had no significant effect on the load-strain relationships of the web of the member. When the joint slipped, the load-strain curves for the various gages indicated a loss in strain but when the load was again increased the load and strain increased until they joined with the original curves.

All of the load-strain curves for the gages located at the center of the I-section are shown in Fig. 19(b). These load-strain relationships increased more or less linearly up to a load of approximately 600,000 lb, after which general yielding started to take place.

Load-strain curves for Specimen S-2 (plain washers) are shown in Fig. 20(a) and 20(b). The outstanding difference between these curves and those for Specimen S-1 (beveled washers) is the increase in the number of times at which a slip occurred. However, the resumption of loading for each increment returned the load-strain relationship to approximately the same position as the corresponding curve for Specimen S-1.

The load-strain curves for Specimen S-3 (riveted) are somewhat smoother but have the same general shape as those of Specimen S-1 and S-2 (see Fig. 21). However, it may be noted that the curves for gages 5, 14, 1, and 16, although in corresponding positions, indicate a considerable difference in behavior. This may have resulted from a difference in the load distribution to the two gusset plates or possibly from a difference in the residual stresses in the member.

The strains at the center section of each specimen have been compared at various loads to determine whether there was any difference in the general behavior of the members. These strain-distribution diagrams are given in Figs.22, 23, and 24, respectively, for Specimens S-1, S-2, and S-3. At the lower loads the strains were relatively uniform but at the higher loads this changed, even in the webs. The diagrams also show that a considerable amount of bending and twisting existed in the flanges of the members.

Similar strain-distribution diagrams have been drawn for horizontal and vertical distribution of longitudinal strain in the web of each specimen. Figure 25(a) shows the strain-distribution diagrams for the horizontal rows of gages in the web of Specimen S-1. Figure 25(b) shows similar diagrams for the distribution along all longitudinal lines of gages on Specimen S-1. Similar diagrams for Specimens S-2 and S-3 are shown in Figs. 26 and 27.

The strain-distribution diagrams for horizontal rows of gages indicate an increase in the shear-lag on transverse sections from the free end of the web to the first row of fasteners. In the diagrams for the longitudinal lines, the increase in axial strains from the last row of fasteners to the first row was nearly linear at the lower loads. This indicates that all fastener rows were taking a nearly equal share of the load. However, at loads greater than the load at the first slip, the strain distributions become curved, indicating that the first few rows of fasteners took a greater share of the load than did the other fasteners.

11. Brittle Lacquer Crack Patterns

The brittle lacquer used in these tests is a strain indicating device which cracks in a direction normal to the principal tensile strain. The sensitivity of the lacquer, the strain at which it cracks, is a function of the type of lacquer used, the temperature and humidity conditions from the time the lacquer is applied until it is used, and the rate of loading during the tests. Consequently, quantitative studies of strains by means of the lacquer require extreme care and the use of carefully developed techniques. Upon completion of the quantitative studies, a valuable qualitative application of the brittle lacquer may be obtained by sensitizing the coating by rapid cooling. This may be accomplished by spraying the specimen with an ordinary carbon-dioxide fire extinguisher and will reveal, in the entire lacquer coating, a crack pattern on all areas and in a direction normal to the principal tensile strains.

The strain indicating lacquer was used on Specimens S-1 and S-3 only. That on Specimen S-1 had a rather low sensitivity. After corrections had been made for creep etc., the sensitivity was found to be slightly over the average yield point strain for the I-section material. Thus, the crack patterns in the lacquer indicated only those locations at which the material had started to yield. The lacquer sensitivity for Specimen S-3 was somewhat better, but still not as high as had been desired. Nevertheless, significant data were obtained from these brittle lacquer studies.

During the testing of Specimens S-1 and S-3 the ends of the cracks in the lacquer were connected with a grease pencil to designate the extent of yielding. These lines were labeled with the load on the specimen at the time the lines were drawn. The crack outlines on

Specimen S-3 are shown in Fig. 28 for the gusset plate and the web and flange of the member for loads up to 500,000 lb. The lower left hand photograph shows also the stress trajectories on the web of Specimen S-3 after it had been sensitized.

The first cracks noted in the lacquer on Specimen S-3 were at the toes of the flanges at the first row of fasteners and on the gusset plate at the seventh row of fasteners. These cracks indicated that local yielding began at these locations at about 240,000 lb. Yielding may have started somewhat before this at the edge of the rivet holes, but because of the interference of the rivet heads, the lacquer could not be placed at the edges of the holes.

The lacquer coatings on Specimens S-1 and S-3 were sensitized at loads of 600,000 lb and 500,000 lb respectively. The general direction of the cracks was marked with a grease pencil and photographed. These so-called stress trajectories on the gusset plates of Specimens S-1 and S-3 are shown in Fig. 29.

The crack extremity outlines at various loads for the Specimen S-1 gusset plate are also shown in the upper part of Fig. 29. The stress trajectories have merely been drawn over the top of these outlines.

12. Residual Bolt Tensions

The residual tensions in the bolts of Specimens S-1 and S-2 were determined after the specimens had failed. A good correlation was found between the residual elongation and the maximum torque necessary to remove the bolts from the first three rows in Specimen S-1. Consequently, torque was used exclusively to determine the residual tensions for the balance of the bolts in Specimen S-1 and Specimen S-2. The average bolt tensions for all seven rows of fasteners in these specimens are shown in Fig. 30.

The bolt tensions in the first row of fasteners of both specimens were small because the I-section material had necked-down at the bolt holes. Similarly, the residual tensions in the seventh row bolts were also low because necking had occurred in the gusset plates at this location. The maximum bolt tensions were obtained in the central portions of the connection. However, even at this location a considerable loss in tension was observed.

It is of interest to note that the average residual bolt tensions were greater in the S-2 specimen than in S-1. Thus, the bolts in the connections without beveled washers appeared to maintain a greater percentage of their initial clamping than did the bolts in the connections with the beveled washers.

IV. ANALYSIS AND DISCUSSION OF TEST RESULTS

13. Behavior of the Specimens

The fact that the bolts in Specimen S-2 were bent, had no consistent effect on the load at which first major slip occurred; both bolted specimens (S-1 and S-2) exhibited first major slip at about 366,000 lb. After this first slip occurred, the behavior of the two specimens differed somewhat. However, these differences in the slip behavior affected only slightly the load and consequently the strain throughout the specimens. When the load in Specimens S-1 and S-2 was increased after a slip, the load-slip and load-strain relationships were merely retraced up to the previous slip load. Thus, the envelopes of the load-slip or the load-strain curves were approximately the same for both bolted specimens.

It has been found that the reactions of the bolts on the gusset plates and the I-beams were inclined slightly with the axis of the specimens. Figure 31 shows one of the gusset plates of Specimen S-2 in the region of the last row of fasteners. The impressions of the threads in the bolt holes and the elongation of the bolt holes indicate the directions of the bolt reactions against the gusset plate during the latter stages of the test. The photographs of the specimen failures, Figs. 7, 8, and 10, show how the holes in the I-section had also been strained at a slight angle with the axis of the web. However, this straining was inclined toward the web in this case, just the reverse of the direction of loading in the gusset plates.

The brittle lacquer studies may be used as a means of estimating the stress concentration factor for the initiation of yielding in the I-section flanges. The initial yielding of the specimens at the first transverse row of fasteners occurred at a load of approximately 240,000 lb and an average nominal stress on the member of 15,000 psi. Then, since the average yield point stress for the material in the toes of the flanges was approximately 40,400 psi (see Table 1), the stress concentration factor for yielding at the toes of the I-section is approximately 2.7.

$$\text{Stress Concentration Factor} = \frac{40,400}{15,000} = 2.7$$

14. Computation of Load Resisted by the Webs

In the analysis of the load-strain data, although not planned originally, an attempt was made to ascertain how much of the total load was resisted by the web at the first row of fasteners. For this purpose average strain distribution diagrams were determined from the strains measured at the first row of fasteners. These average strain distribution diagrams are shown in Fig. 32. When the distribution of axial strain across the web is known, the approximate axial stress distribution may be determined from the stress-strain properties of the material. These axial stresses may then be used to estimate the total load carried by the web.

To compute the load resisted by the web at various loads on the specimens, reference was made to the average strain distribution diagrams of Fig. 32. In Specimen S-1, for example, consider the distribution of strain at a total load of 300,000 lb. The "strain-area" (the area under the strain distribution diagram), for this load is made up of the trapezoidal areas ABFC and BIKF. The sum of these areas divided by the web depth is then equal to the average strain in the web at the given load.

The average stress may be computed from the relationship,

$$s_w = \epsilon_w E \qquad (1)$$

Then the load carried by the web is:

$$P_w = s_w A_w \qquad (2)$$

where,

ϵ_w = average unit strain in the web

E = modulus of elasticity, assumed to be 30,000,000 psi

P_w = load resisted by the web in lb

s_w = average stress in the web in psi

A_w = area of the web in sq. in.

On this basis the load resisted by the web of Specimen S-1 at the first transverse row of bolts was found to be 136,000 lb at a total load of 300,000 lb.

As the loads became higher, the axial strains in the web approached and then exceeded the yield point strains of the web material. When the web strains at a gage exceeded the yield point strain it was assumed that the material from that point out to the nearest flange was stressed at the yield point stress. In Fig. 32 the average variation in yield point strain from the original coupon data has been plotted on the strain distribution diagrams. Thus, at a total load of 450,000 lb the strain area for the web of Specimen S-1 would be the sum of the areas LMQC, OPKR, and the two trapezoidal areas MNFQ, and NORF. Then, in the same manner as before, the load carried by the web was found to be 269,000 lb and the load carried by the flanges was 181,000 lb.

If the web and flange material of Specimen S-1 had been strained to the same extent, that is uniformly, they would have resisted a portion of the total load in proportion to their respective areas (216,000 lb in the web). Then, both the flanges and the web would have been fully effective, or 100 percent efficient, in resisting the load.

In the present study the effectiveness of the web has been computed as follows:

$$\text{Web effectiveness, percent} = \frac{P_w/A_w}{P/A_g}(100) = \frac{100s_w}{S} \qquad (3)$$

Where P = load on the specimen in lb

A_g = gross area of 18"-I-54.7 lb section

S = average stress on the gross section in psi

When the web material is, in part, strained above the yield point, the load carried by the web may be computed on the basis of yield point stress on those areas which have yielded. This procedure was used to determine effectiveness of the web material of the specimens for loads up to about 500,000 lb. Beyond this load, the web material started to strain-harden and the computed effectiveness of the web may be somewhat too low. However, the effect should not be too great until all the material in the section is in the strain-hardening state. After all of the material in the web begins to work-harden, the assumption that the web is at yield point stress level may be considerably in error.

The variation in web effectiveness with load for the three specimens of this study are shown in Fig. 33. In this figure it may be seen that the behavior of the three specimens differed somewhat in the early stages of the tests. At the small loads before local yielding or slip occurred, the effectiveness of the webs appeared to depend on the type of fastener used in the connection. In the web of Specimen S-3, the specimen with rivets, the strain gradient across the section was more uniform than in the bolted specimens and, as a result, the web was more effective in resisting the applied loads than in the case of the other two specimens. The bolts in the specimen with beveled washers, Specimen S-1, appeared to distribute the load more uniformly than did the bolts in the specimen with plain washers. Consequently, in the early stages of the tests, the web of Specimen S-1 was somewhat more effective than the web of Specimen S-2.

Beyond 300,000 lb the webs of the three members appeared to act somewhat alike but, at times, were quite erratic in the bolted members because of the slip in the joints. When the toes of the I-section began to yield a greater share of the total load was resisted by the web of each specimen. This, of course, produced an increase in the web effectiveness. Then, as general yielding progressed through the flanges the webs became increasingly more effective until work-hardening began. As work-hardening progressed across the webs, the effectiveness of the webs appeared to decrease.

It should be noted that the straight line approximations used for the strain distributions of Fig. 32 may be somewhat in error for loads greater than 350,000 lb. However, the available data do not seem to justify any further refinements.

15. Effectiveness of Webs at Failure

When the test specimens failed the fracture occurred through the net section of only one of the two joints in the members. If it is assumed that failure in the other joint was incipient, the effectiveness of the parts of the I-section can be obtained from the properties of the material at the critical section of the unfractured joint.

The properties of these intact joints were studied by means of coupons which were cut from the critical section (first transverse row of fasteners). Seven of these coupons were taken from the web at the first transverse row of fasteners of each of the three specimens. These coupons were milled flat and tested using a 2-in. high sensitivity extensometer to determine accurately the "break" (defined as the yield strength) in the stress-strain curves for these retest coupons.

When the original coupons from the I-section material were tested, the actual least cross-sectional areas were determined at each load increment. From these data the "true stress" (based on the least area at the increment) and the "nominal stress" (based on the original coupon area), were ascertained. By comparing the original stress-strain curves and the stress-strain curves of the retest coupons it has been possible to determine approximately the effectiveness of the webs when failure occurred in each companion connection.

The principal step in determining the efficiency and effectiveness of the web was to determine the magnitude of stress in the web when the member failed. The manner in which this was done may be seen in Fig. 34. The material across the critical section of the unfractured connection was strained into the work-hardening range during the test. This resulted in a reduction in the thickness of the material at the section used for the re-test coupons. Consequently, the yield strengths determined from the re-test coupons correspond to points on the "true stress-strain" curves of the original material. The initial strain or position of the origin of the "stress-strain" curves of the re-test coupons as compared with the original curves of the material was determined by sliding the curves over the "true stress-strain" curves until the yield strength coincided with the latter curve. When the yield strength of the re-test coupons was located on the "true stress-strain" curves, the nominal strain could be ascertained. This nominal strain then gave the maximum engineering stress to which the material had been subjected during the test of the member and can be used to determine the magnitude of the load carried by the web of the member at failure.

The yield strengths of the re-test coupons of Specimens S-1, S-2, and S-3 are shown in Fig. 35. It is evident in this diagram that the yield strength, and consequently, the strains at failure were very nearly the same across the web of Specimens S-1 and S-2. The yield strength distribution for Specimen S-3 was different, but it should be remembered that the material in Specimen S-3 was riveted first and then bolted after the rivets had failed in shear. This multiple testing and re-fastening with bolts undoubtedly had an influence on the strain distribution in the web at failure.

The estimated axial stresses across the critical section of Specimens S-1, S-2, and S-3 at failure are shown in Fig. 36. The ultimate strengths of the original coupons from this section are also plotted in the diagram. From these data it appears that the rupture occurred when the maximum stress in the web near or at the web-flange junctions reached the minimum ultimate coupon strength. This observation is similar to observations which have been made in other tests of flat plate specimens and may aid greatly in explaining the behavior of structural joints at failure.

If a joint fails when some portion of the section is stressed to its ultimate strength, then the ultimate strength (as determined from the original coupons) could be used to compute the efficiency of the joint or member. The efficiencies of the specimens of this program, if it is assumed that the joints failed when the minimum ultimate coupon strength of 67,700 psi was attained, were as follows:

Specimen No.	Test Efficiency in Percent
S-1	73.9
S-2	74.9
S-3	70.4 (first loading) 75.7 (second loading) 80.6 (third loading)

Although the member with plain washers (S-2) was slightly stronger than the joint with beveled washers (S-1) the difference is not believed to be significant. Differences as large or larger may result from variations in the properties of the material itself. The higher efficiency of the riveted specimen may have resulted from the cold working of the joint produced in the multiple loadings. Thus, the efficiency of the specimens of this series may be taken as the average of Specimen S-1 and S-2, or 74.4 percent.

With the data available the efficiencies may be broken down into the efficiencies of the components of the section, the web and the flanges. The efficiency of the web of the specimen is the ratio of the load resisted by the web at failure to the computed ultimate web resistance.

In a similar manner, the efficiency of the flanges can be determined.

The efficiency of the webs at failure were determined from the areas under the "engineering-stress" distribution diagrams of Fig. 36. Then the efficiencies of the flanges of each specimen could be computed, because the flange efficiency times the flange area plus the web efficiency times the web area must equal the test efficiency of the specimen times the gross area of the section. On the basis of this relationship the efficiencies of the component parts of the I-section of the three specimens were found to be as follows:

Specimen No.	Specimen Test Efficiency in Percent	Web Efficiency in Percent	Flange Efficiency in Percent
S-1	73.9	80.9	67.4
S-2	74.9	82.8	67.6
S-3	80.6	74.1	86.6

Theoretical Efficiency = 83.6 percent

Neglecting Specimen S-3 because of the multiple loading, one finds that the webs were approximately 82 percent efficient even though there were no holes in them; the flanges were about 67.5 percent efficient and the net area of the flanges was about 68.8 percent of the gross area of the flanges. Thus the flanges almost developed the full strength of the flange material as determined by the coupon tests, whereas the web material developed only 82 percent of the strength of the material.

V. SUMMARY OF RESULTS AND CONCLUSIONS

16. Summary of Results

The results of the tests of the three specimens of this series may be summarized as follows:

1. The two bolted specimens behaved similarly up to approximately 366,000 lb, the average load at first major slip. After this first slip, however, the behaviors differed somewhat. Specimen S-1 (beveled washers) exhibited only two large slips at nearly equal loads, before both joints of the specimen had pulled into full bearing. Specimen S-2 (plain washers), experienced a slip in one joint at 368,000 lb, but the second joint did not slip until the load had reached 520,000 lb.

The load slip relationships of the riveted Specimen, S-3, are smooth curves in contrast to the irregular load-slip diagrams obtained for the bolted joints.

2. All of the fasteners in the connections seemed to slip as a unit; the slip did not propagate gradually along the length of the joint.

3. Up to a unit shearing stress of 17,800 psi (a total load of 300,000 lb) the slip was greater in the riveted specimen than in either of the bolted specimens, but beyond this stress the slip in the bolted joints was larger.

4. The load-strain curves for the specimens indicate that major slips in the joints had no great effect on the strains in the web of the members.

5. The load-strain relationships from the web gages at the center section were more or less linear up to loads of approximately 600,000 lb. Beyond this load yielding became general throughout the entire section.

6. The strain-distribution within the joints, as one might expect, indicated that the shear-lag in the web increased from the free end of the web to the first transverse rows of fasteners, and that the material at the center of the web at the first transverse row of fasteners was never utilized as fully as the flange material at this section.

7. The strains from the longitudinal lines of web gages near the flanges of the joints indicated a nearly linear pick-up of axial stress in the webs of the bolted specimens before first slip. After slip, however, the distributions became curved, indicating that the first rows of fasteners were carrying a greater share of the load than those in the last rows.

8. The brittle lacquer studies indicated that local yielding had started in the toes of the flanges at the first transverse rows of fasteners at a load of approximately 240,000 lb. The computed stress concentration factor at this location is then approximately 2.7.

9. The load-strain relationships from the SR-4 gages on the webs of the specimens were used to ascertain the magnitude of the load resisted by the webs. From this analysis it was observed that, at low loads, the web of each specimen was less effective than the flanges. But when yielding was general across the entire critical section, the webs were considerably more effective in resisting load than were the flanges.

10. The maximum loads resisted by the specimens were 798,000 lb for Specimen S-1, 808,000 lb for Specimen S-2, and 870,000 lb for Specimen S-3.

The rivets in the two joints of Specimen S-3 (riveted) failed in shear at 760,000 lb and 818,000 lb. These loads correspond to an average ultimate shearing stress of 45,000 and 48,600 psi, respectively on the rivets. All of the rivets, after failure, were replaced with high strength bolts to obtain the fracture in the main member.

11. The analysis of the specimens indicates that, at failure, the web material at the critical sections of the bolted specimens was approximately 82 percent efficient, and the flanges about 67.5 percent efficient. The web efficiency for the riveted specimen was 74.1 percent, and the flange efficiency was 86.6 percent. However, the behavior of the riveted specimen was probably affected by the multiple loadings necessitated by the rivet failures in this test.

19. Conclusions

The limited tests described in this report lead to the following conclusions for the behavior of I-beam tension connections.

1. The principal difference in the behavior of the bolted joints with or without beveled washers was in the manner in which the joints slipped into bearing. The joints assembled with beveled washers slipped into full bearing at loads only slightly greater than the load at first major slip while one of the joints with only flat washers required a load considerably greater than the load at first major slip to pull into bearing. Thus, there may be advantages other than the

reduction in cost by assembling joints without beveled washers. However, further testing is necessary to demonstrate whether the beveled washers are necessary under other conditions than the few considered in these tests.

2. The distribution of strains throughout the sections were not greatly affected by the variation in the type of fasteners. In the early stages of the tests, however, the rivets did appear to provide a somewhat more uniform distribution of load throughout the web than did the bolts, and the bolts with the beveled washers appeared to give a little more uniform distribution than did the bolts with the plain washers.

3. The strength of the joints of this study appeared to depend upon the minimum ultimate strength of the material. The material of minimum ultimate strength in an I-section will generally be located at the junction of the web and flanges.

4. Although the flanges in these truss-type connections developed most of the strength in the available material, the reduced efficiency of the web material resulted in test efficiencies which were approximately 10 percent less than the theoretical (net section) efficiencies.

5. Although many questions may be answered by these few tests, it would seem desirable to pursue further the studies developed herein concerning the efficiency of the components of structural members and shapes. Such studies could be used to answer such questions as:

a) What is the effect of the web depth on the efficiency of the I-section?

b) Is the web efficiency a function of the relative areas of the web and flanges?

c) What effect does the web have upon the efficiency of a flange?

d) Do the mechanical properties of the material affect the web efficiency?

e) How do the efficiencies of wide-flange and standard I-sections differ?

These are but a few of the many questions that might be asked about the efficiency of truss-type members.

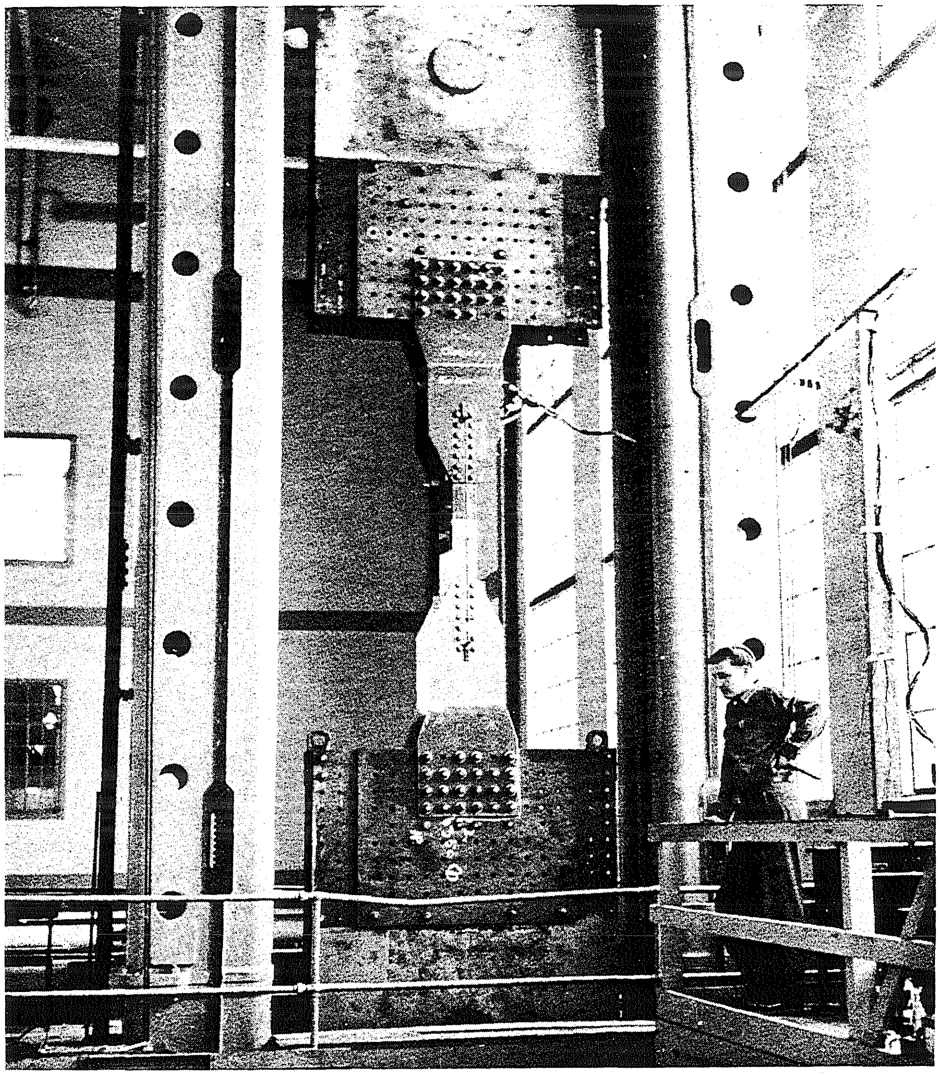
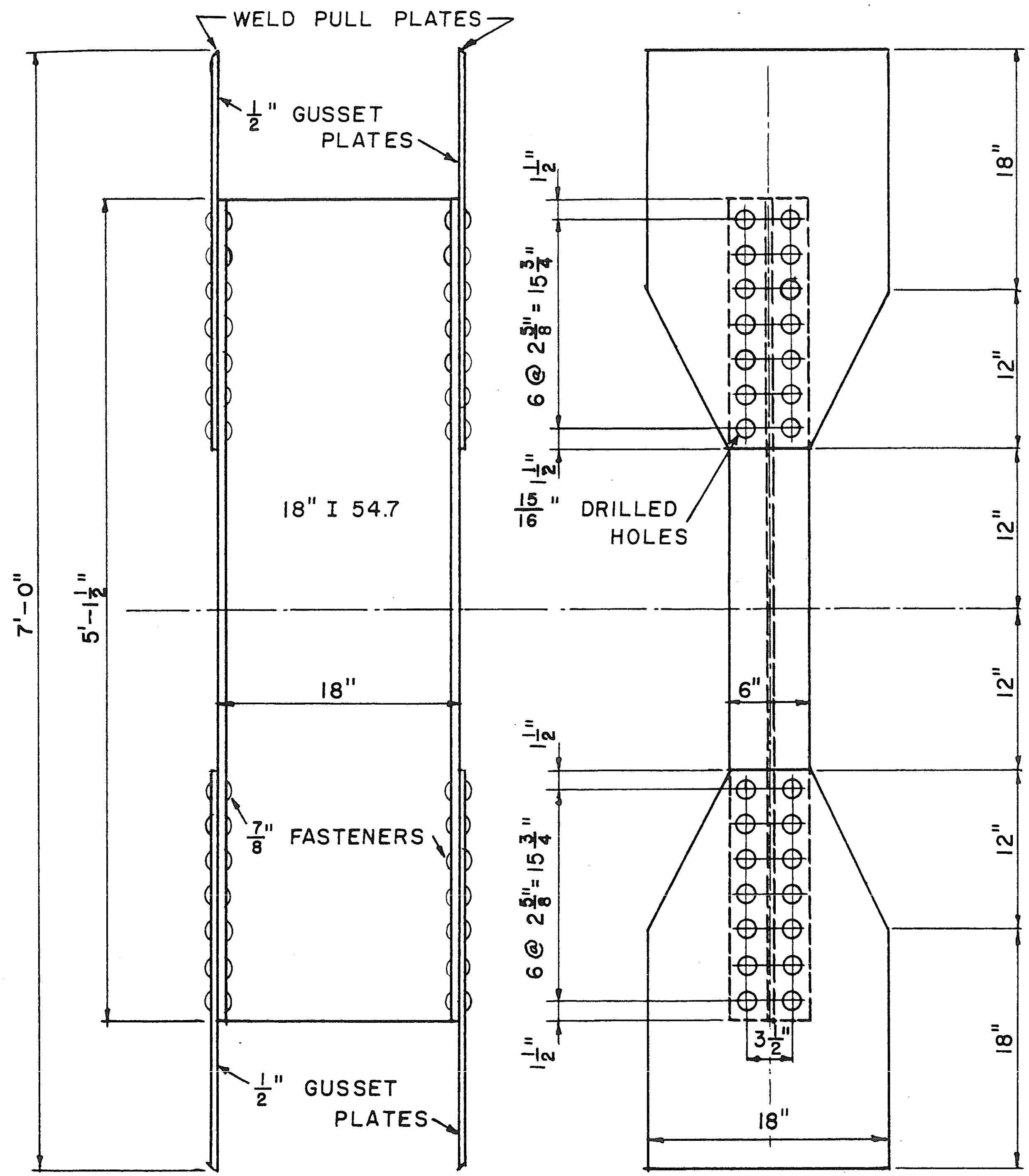
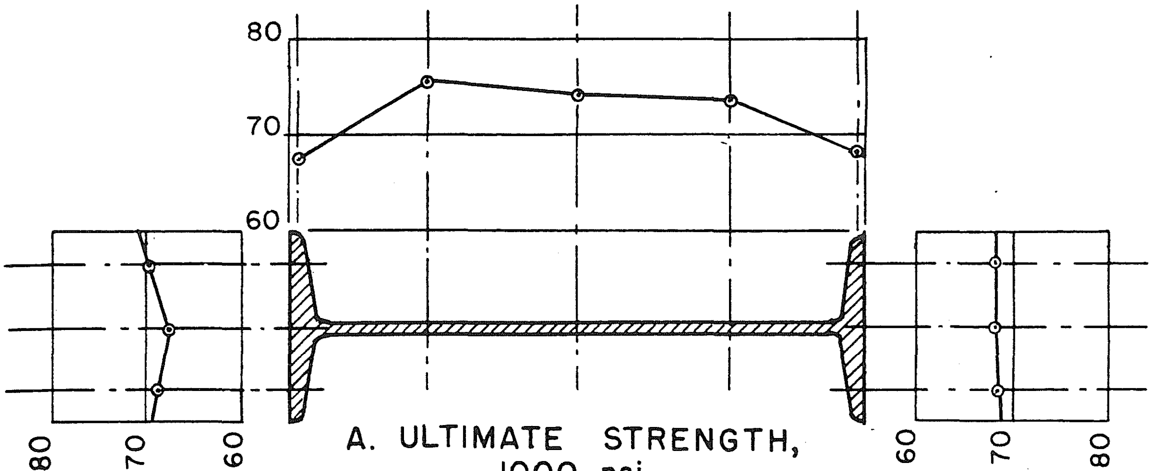


FIG. 1 TEST ASSEMBLY IN 3,000,000 LB. MACHINE

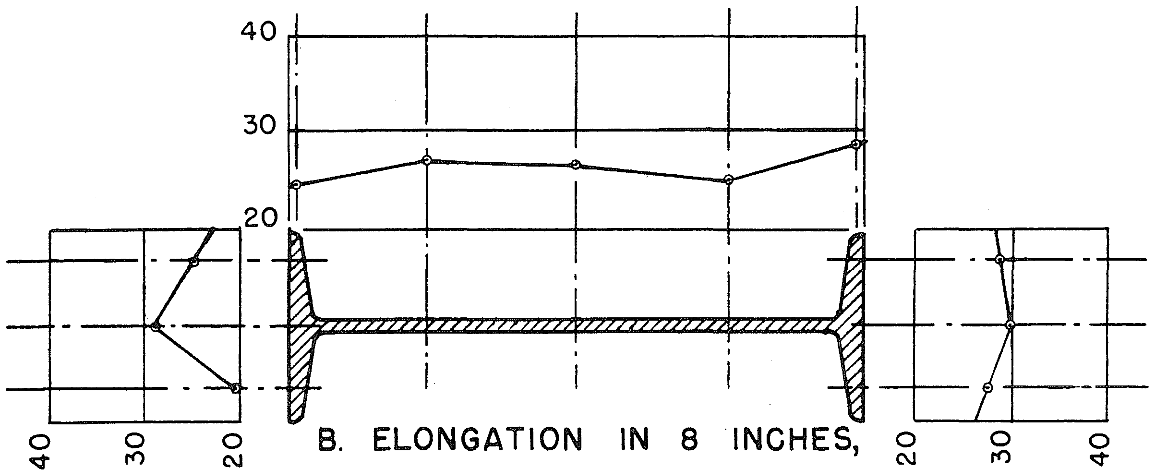


SPECIMEN	FASTENERS
S-1	BOLTED, BEVELED WASHERS
S-2	BOLTED, PLAIN WASHERS
S-3	RIVETED

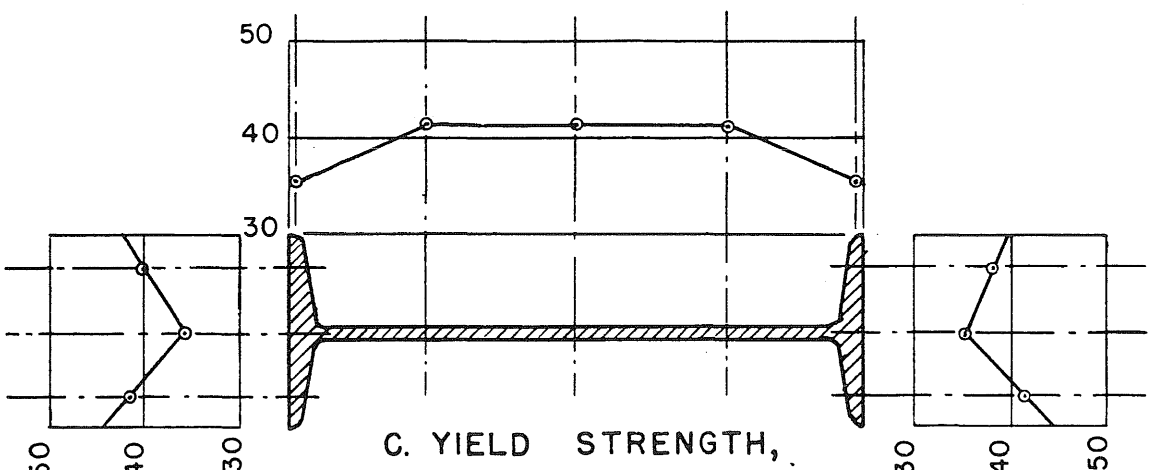
FIG. 2 DETAILS OF TEST SPECIMENS



A. ULTIMATE STRENGTH, 1000 psi.

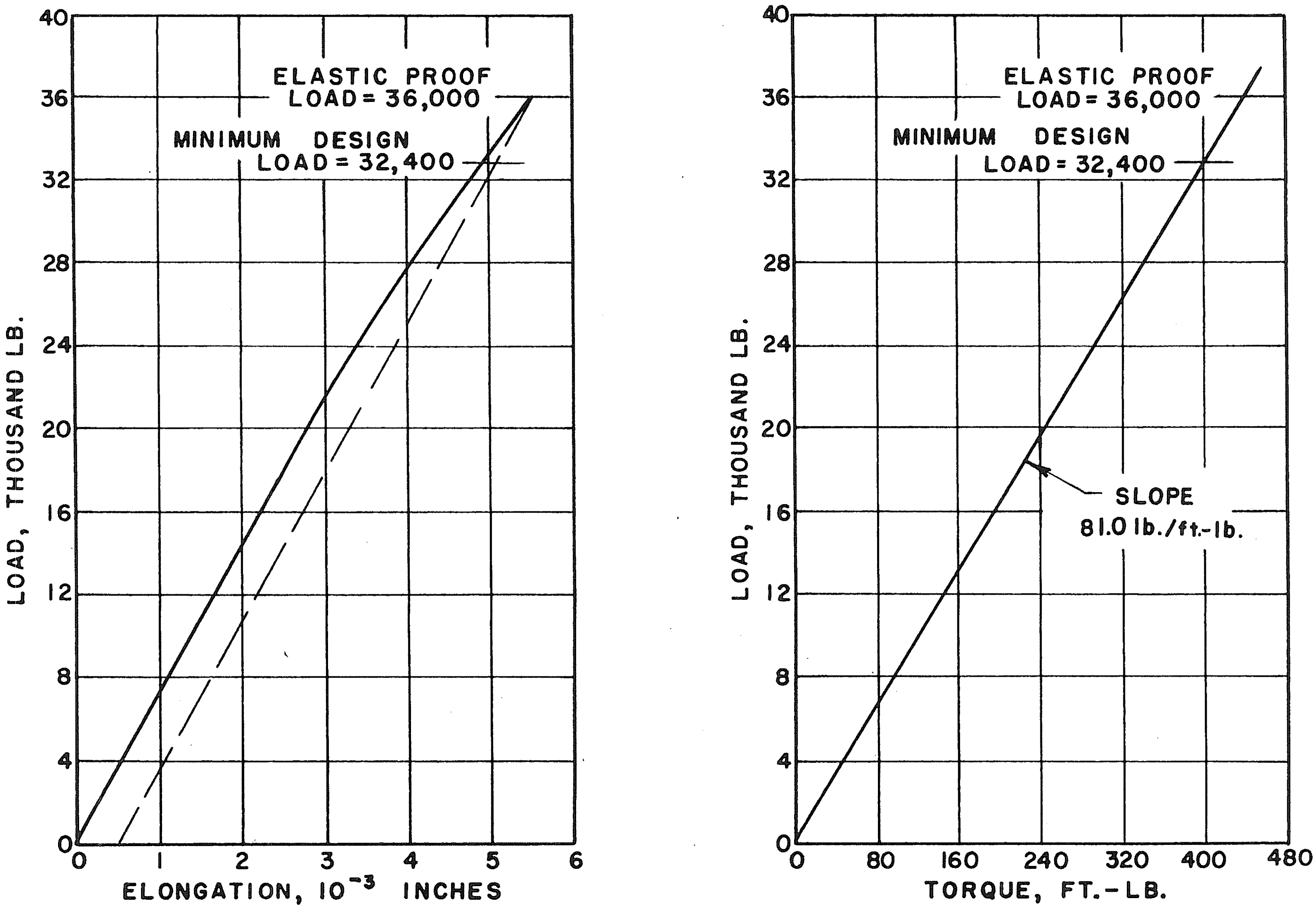


B. ELONGATION IN 8 INCHES, PER CENT



C. YIELD STRENGTH, 1000 psi.

FIG. 3 MECHANICAL PROPERTIES OF 18"-I-54.7



(a) AVERAGE LOAD-ELONGATION CURVE
SPECIMEN S-1

(b) AVERAGE LOAD-TORQUE CURVE
SPECIMEN S-2

FIG. 4 BOLT CALIBRATION CURVES

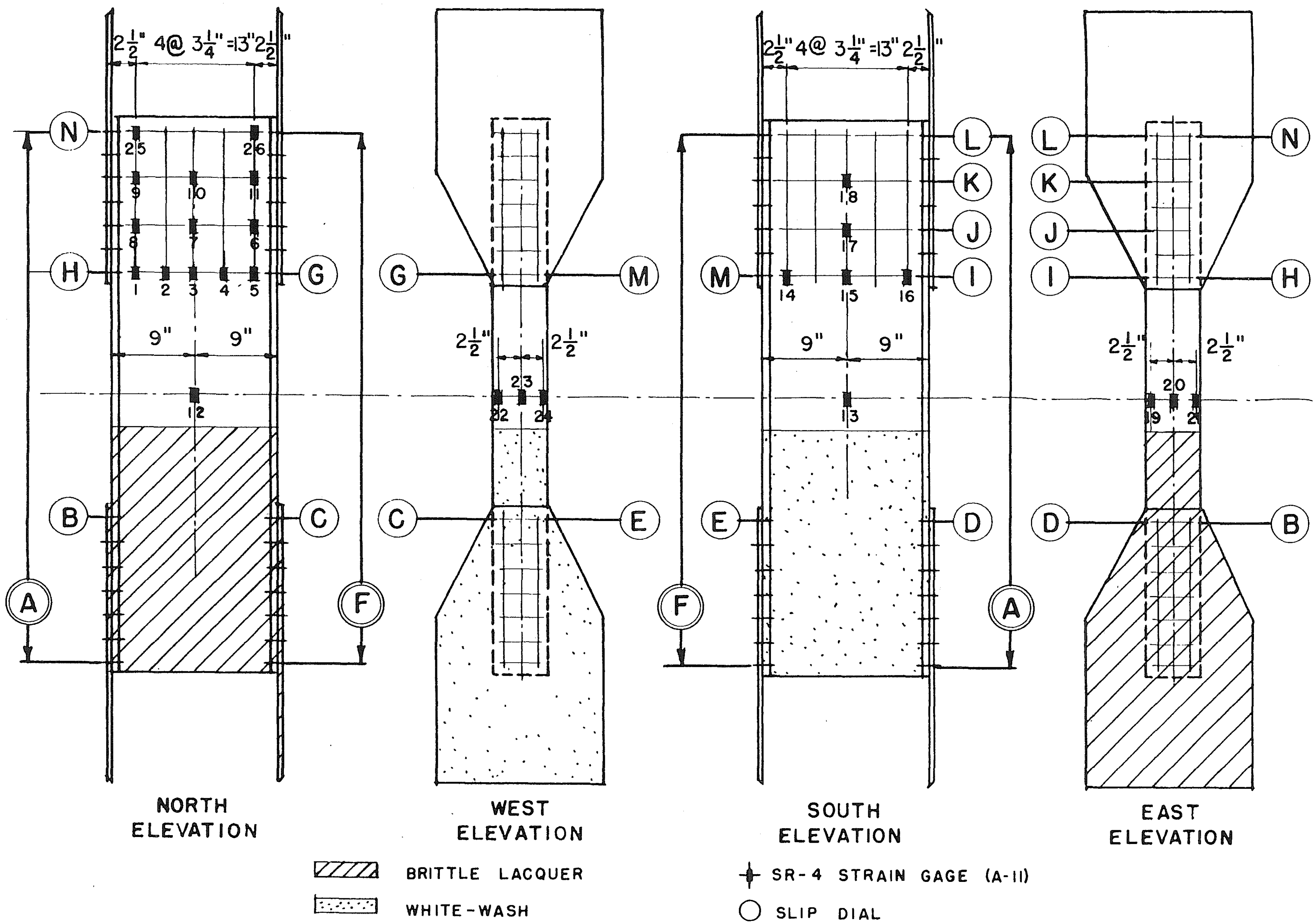


FIG. 5 LOCATION DIAGRAM FOR STRAIN AND SLIP MEASUREMENTS

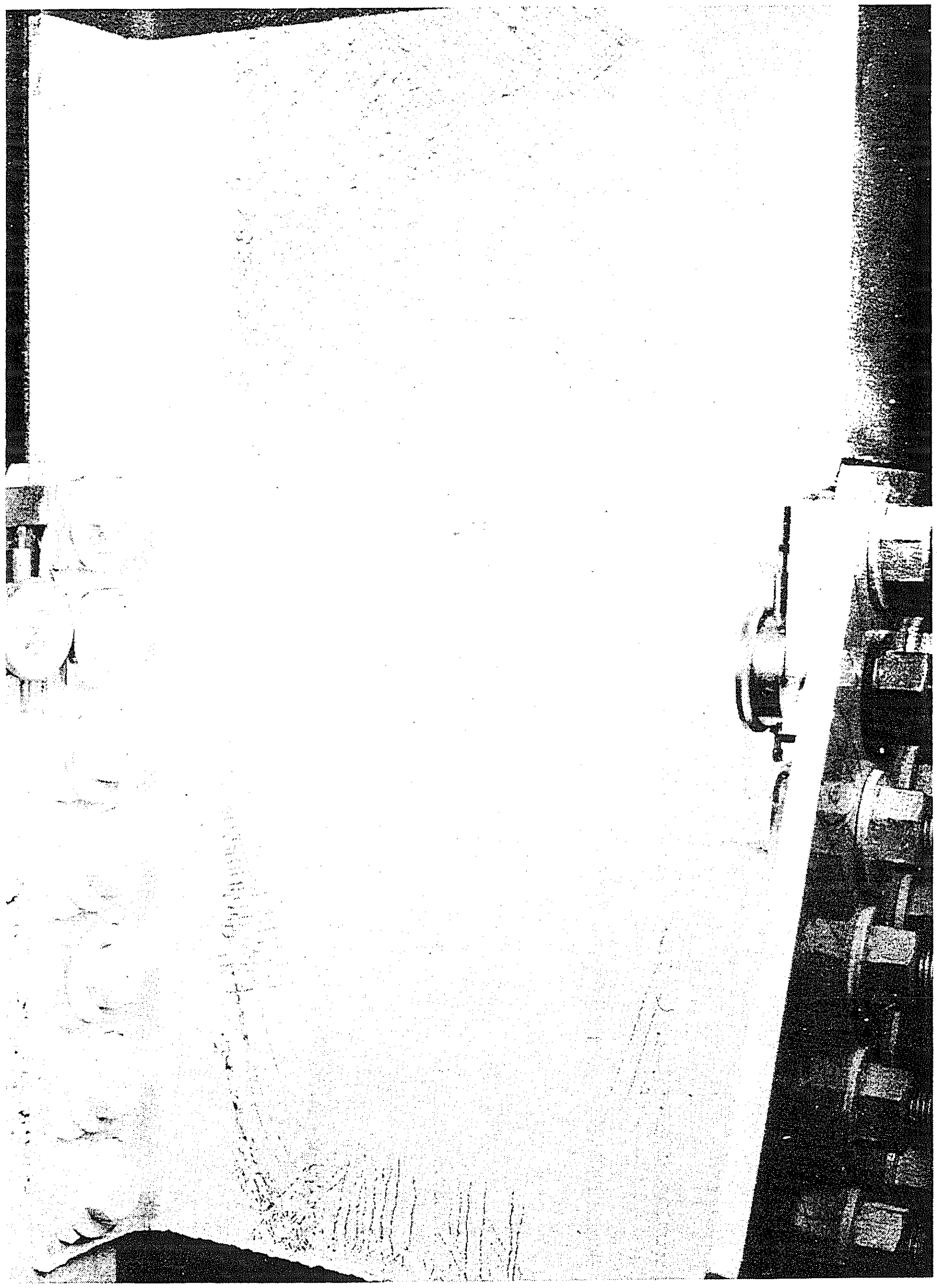


FIG. 6 LÜDERS' LINES ON WEB OF SPECIMEN

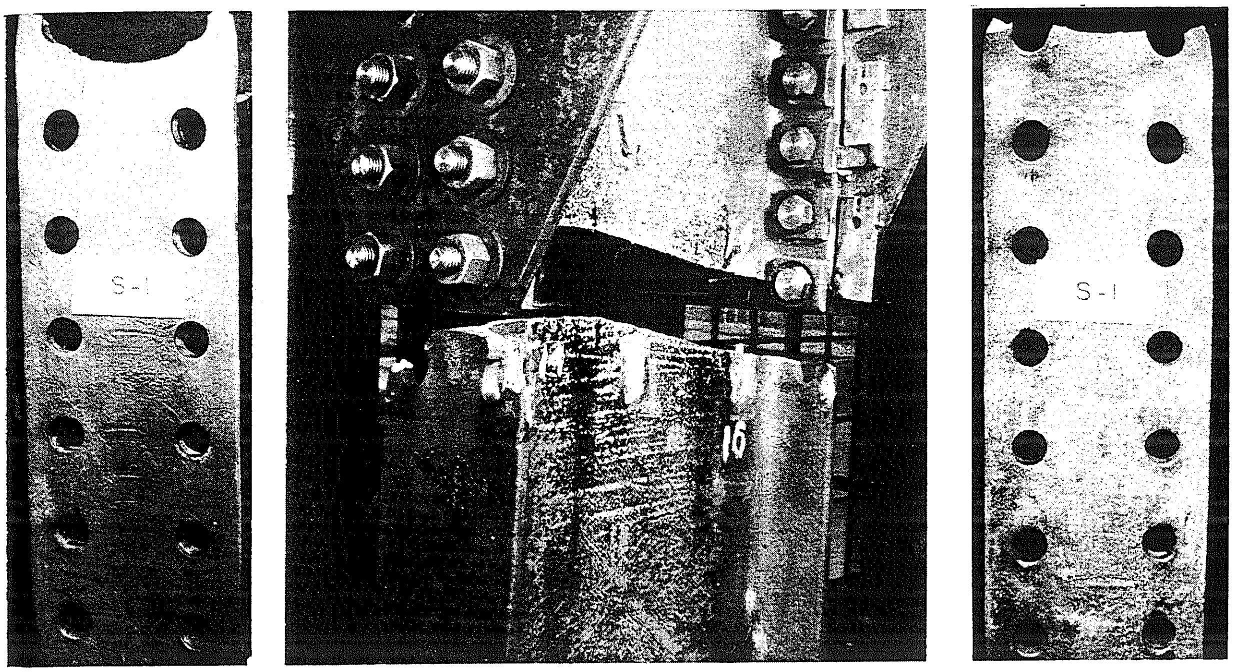


FIG. 7 FRACTURE OF SPECIMEN S-1

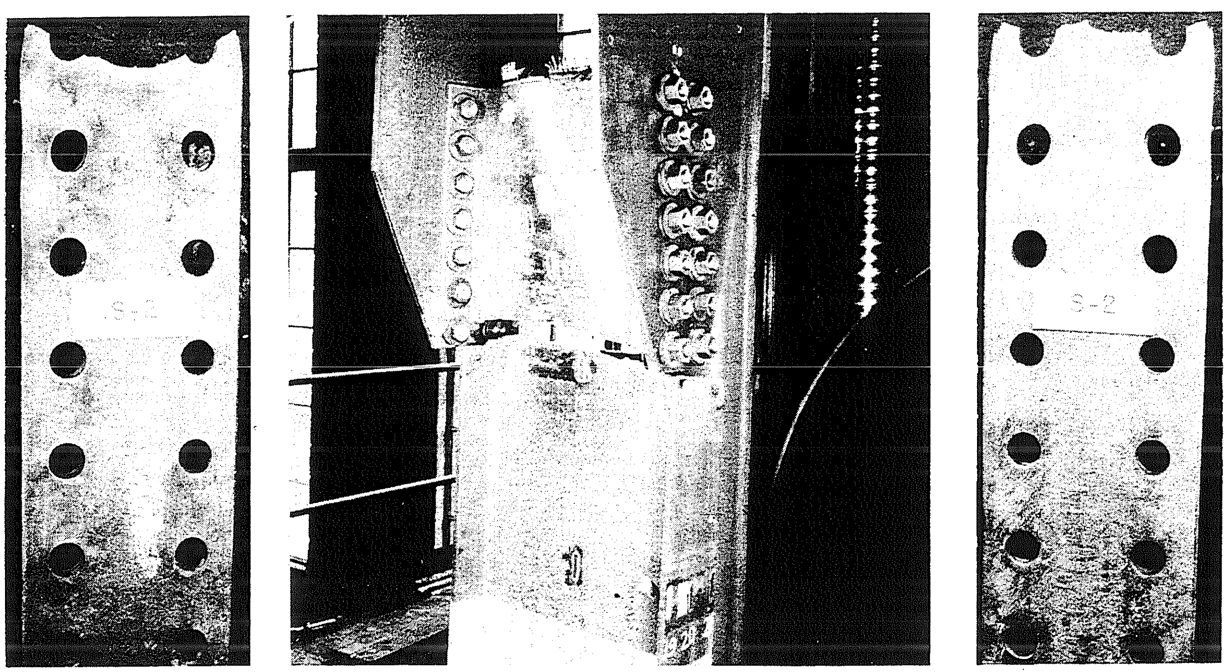
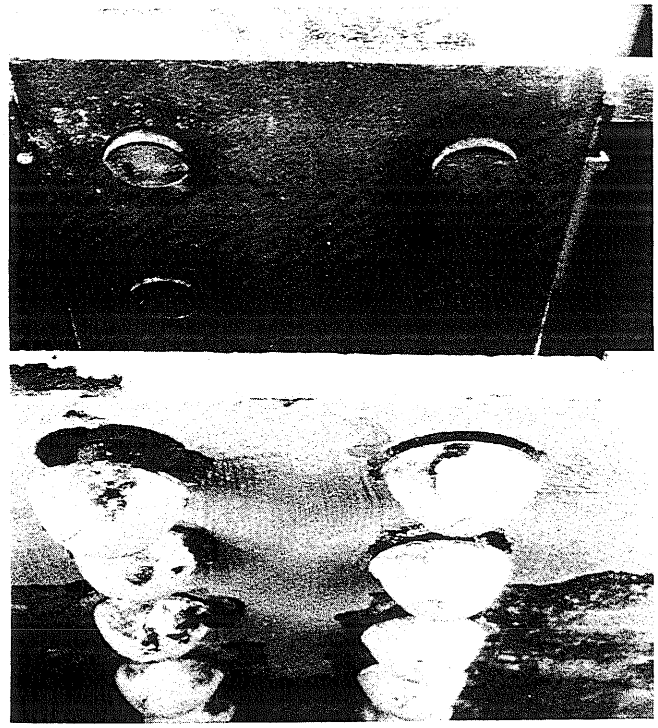


FIG. 8 FRACTURE OF SPECIMEN S-2



(a) FIRST FAILURE AT 760,000 LBS.

(b) SECOND FAILURE AT 818,000 LBS.

FIG. 9 SHEAR FAILURES OF SPECIMEN S-3

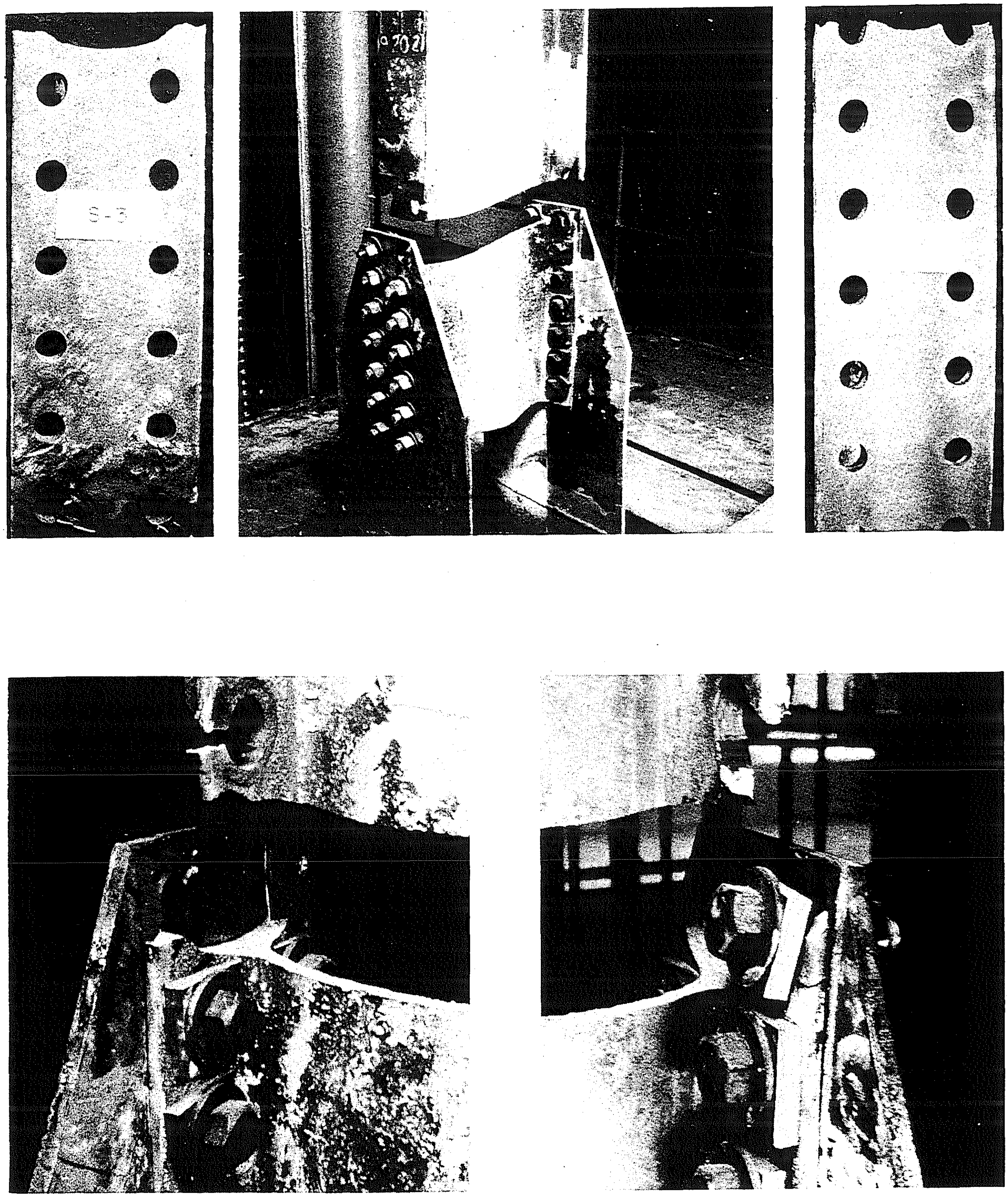


FIG. 10 FRACTURE OF SPECIMEN S-3

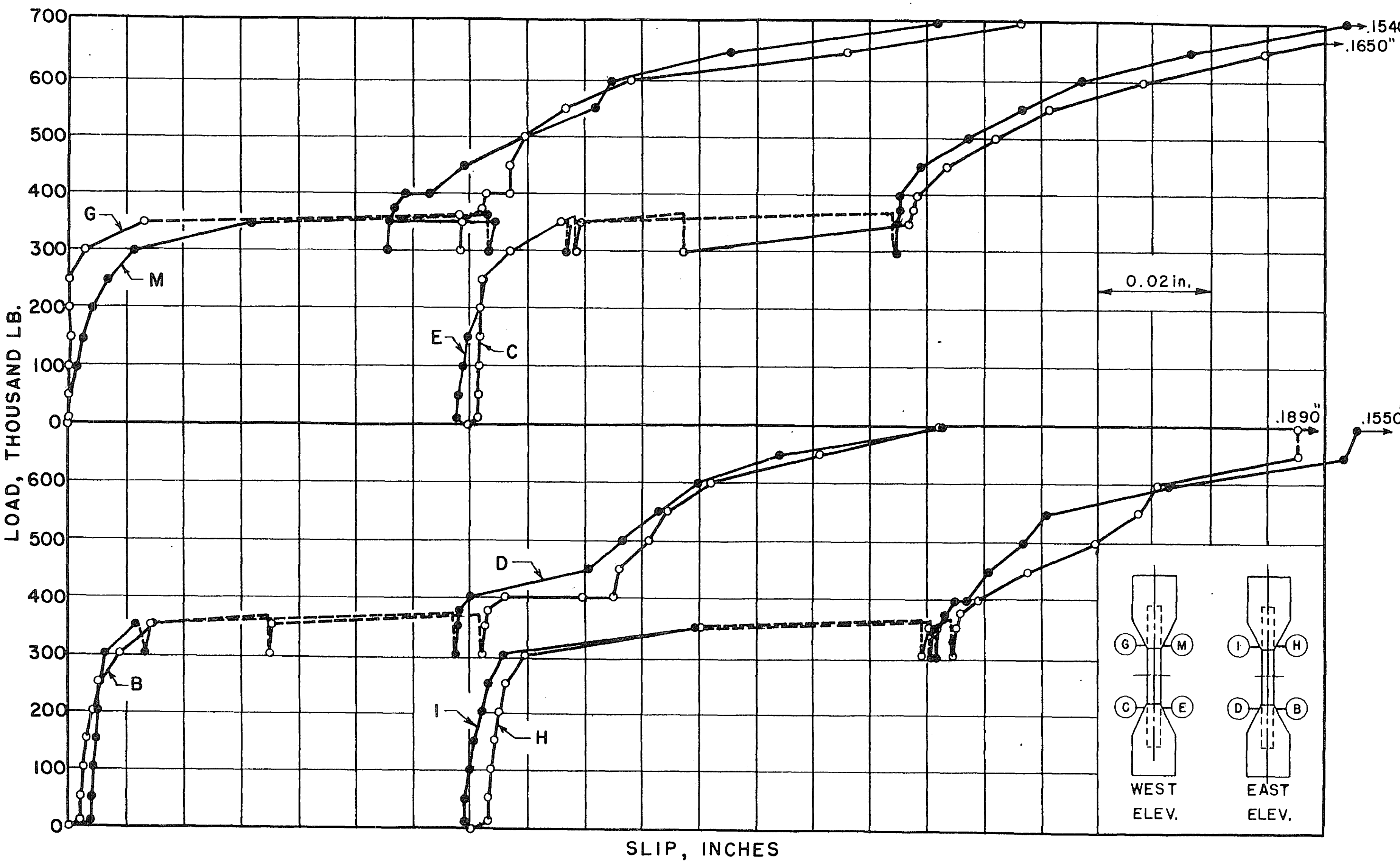


FIG. 11 LOAD-SLIP CURVES AT FIRST ROW OF FASTENERS OF SPECIMEN S-1

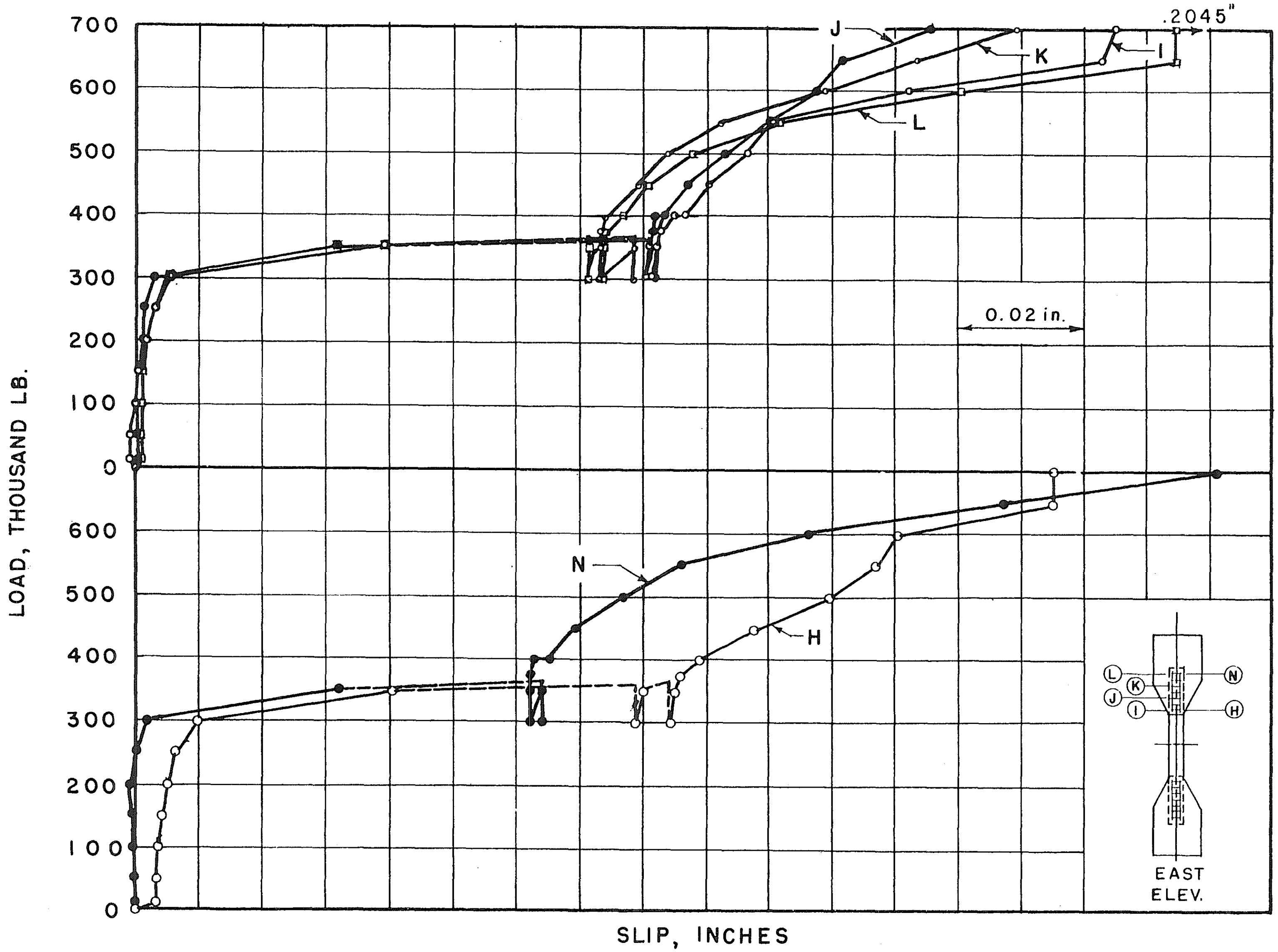


FIG. 12 LOAD-SLIP CURVES FOR FASTENERS IN A LINE, SPECIMEN S-1

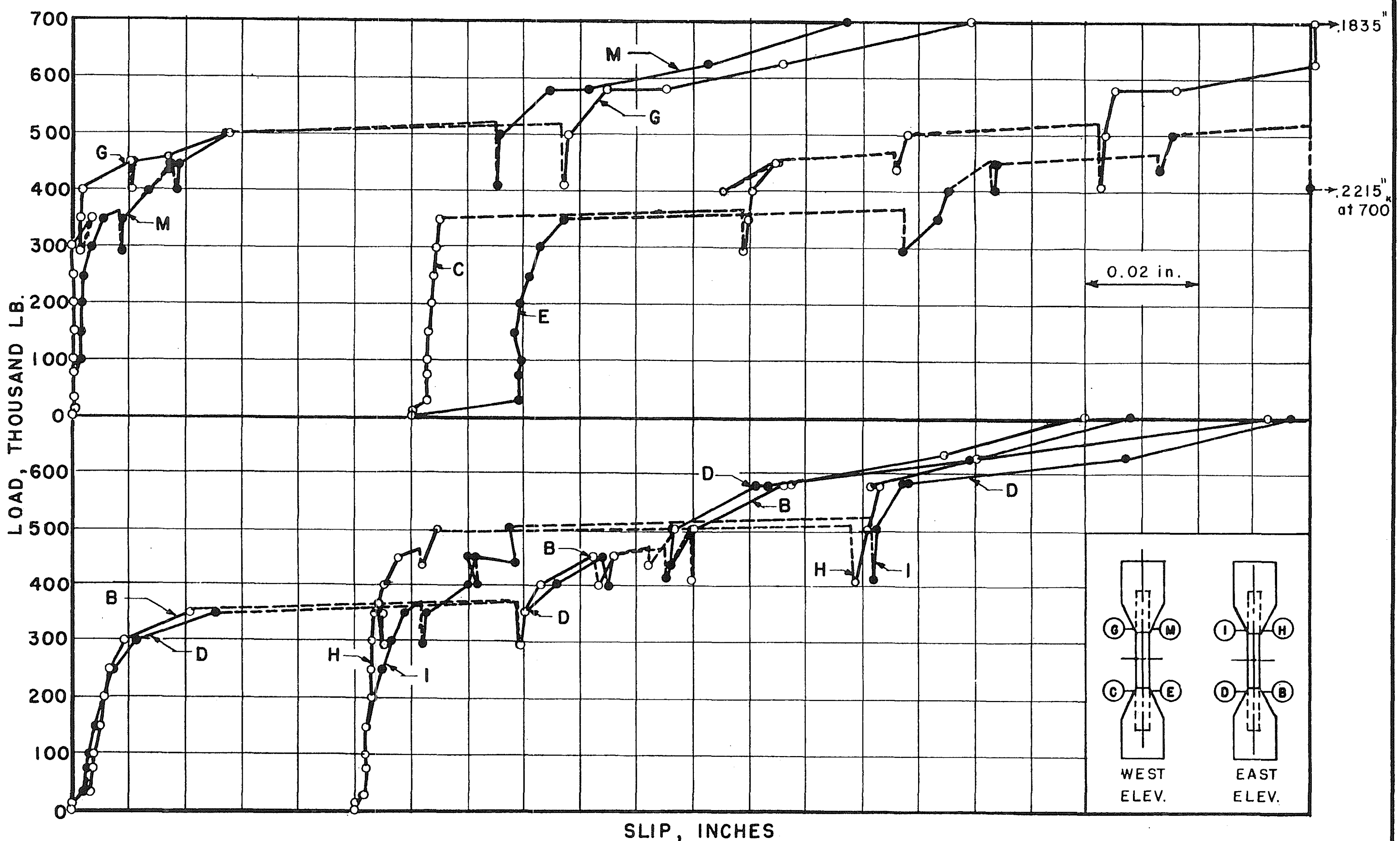
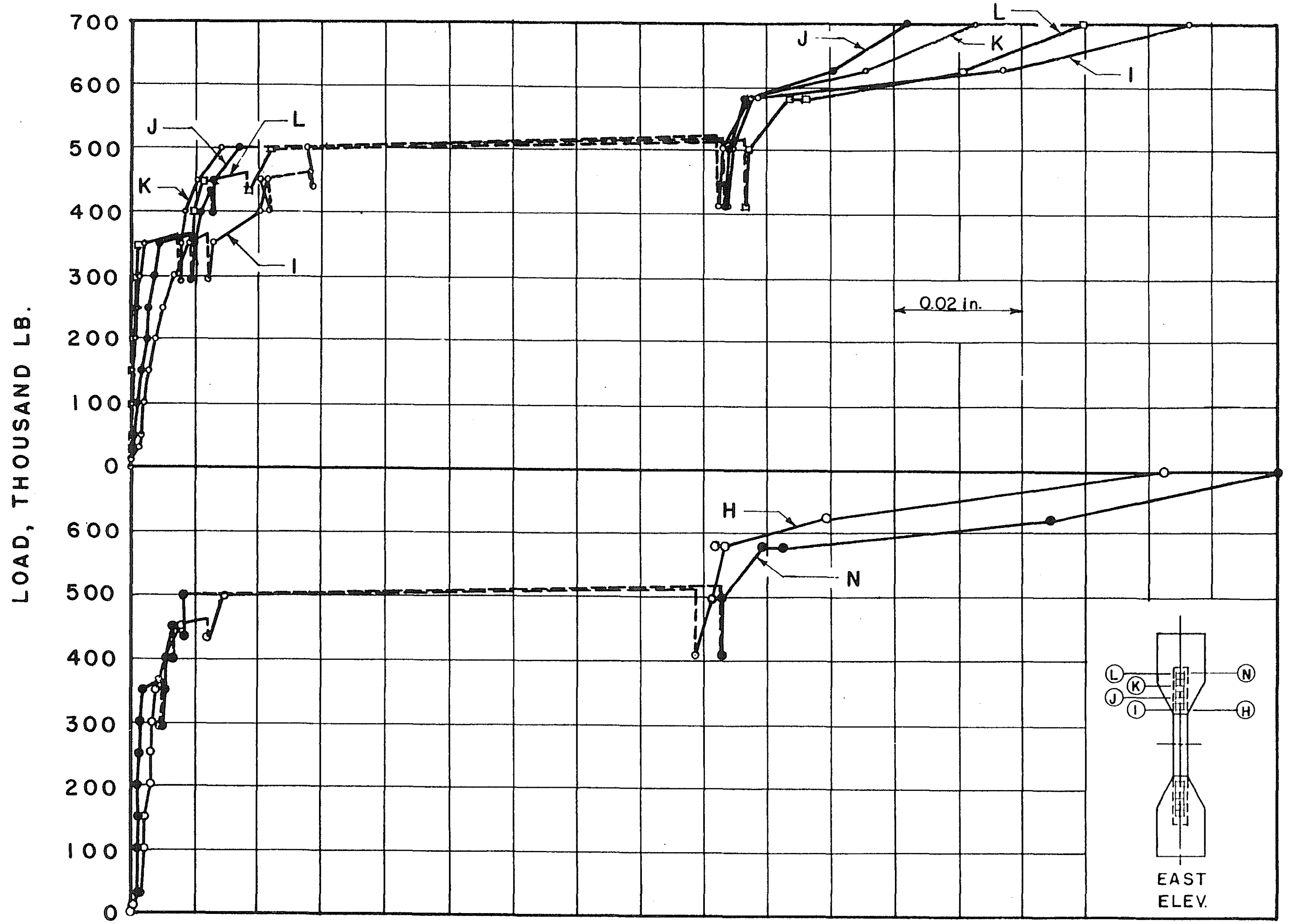


FIG. 13 LOAD-SLIP CURVES AT FIRST ROW OF FASTENERS OF SPECIMEN S-2



SLIP, INCHES

FIG. 14 LOAD–SLIP CURVES FOR FASTENERS IN A LINE, SPECIMEN S-2

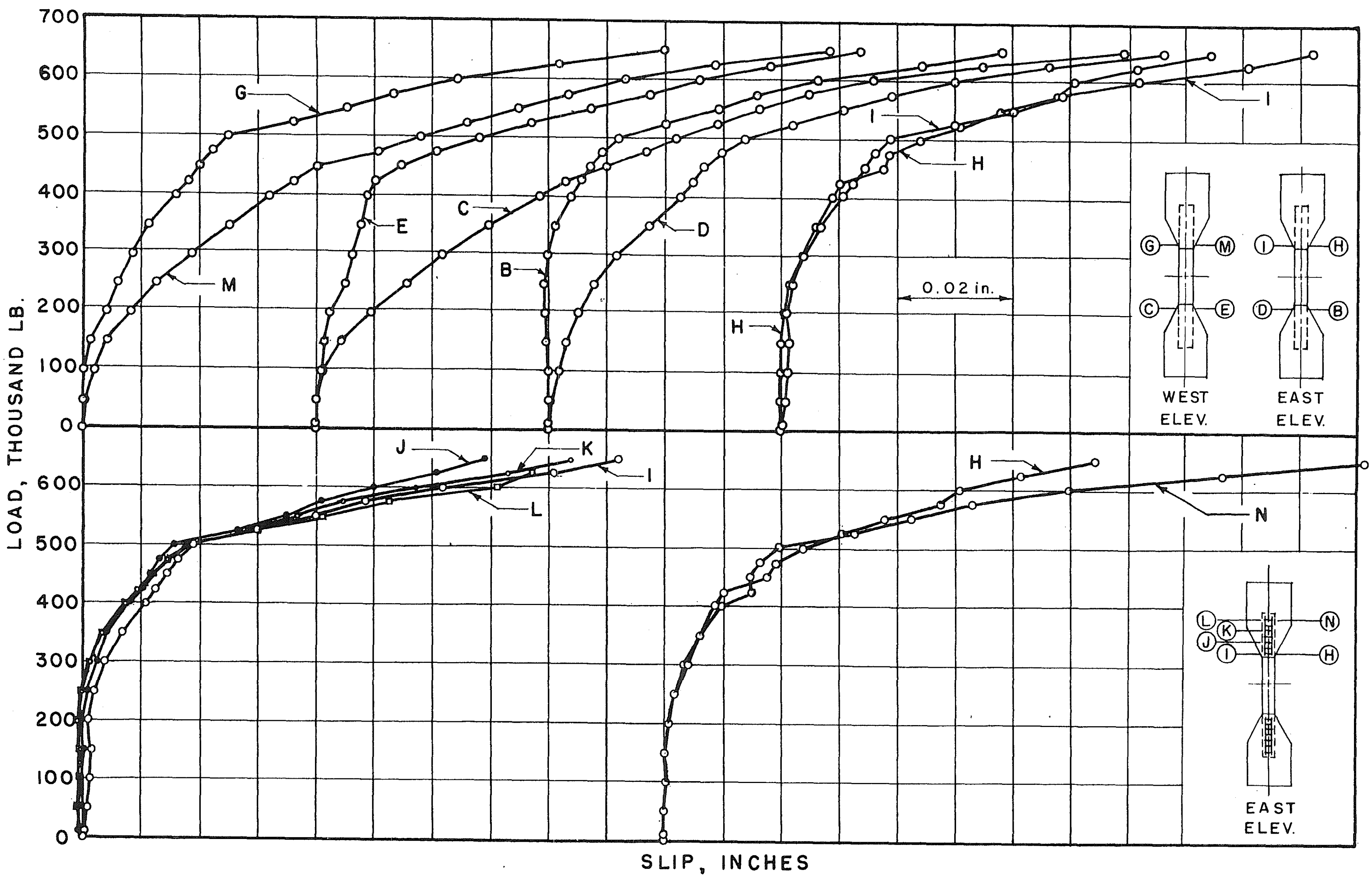
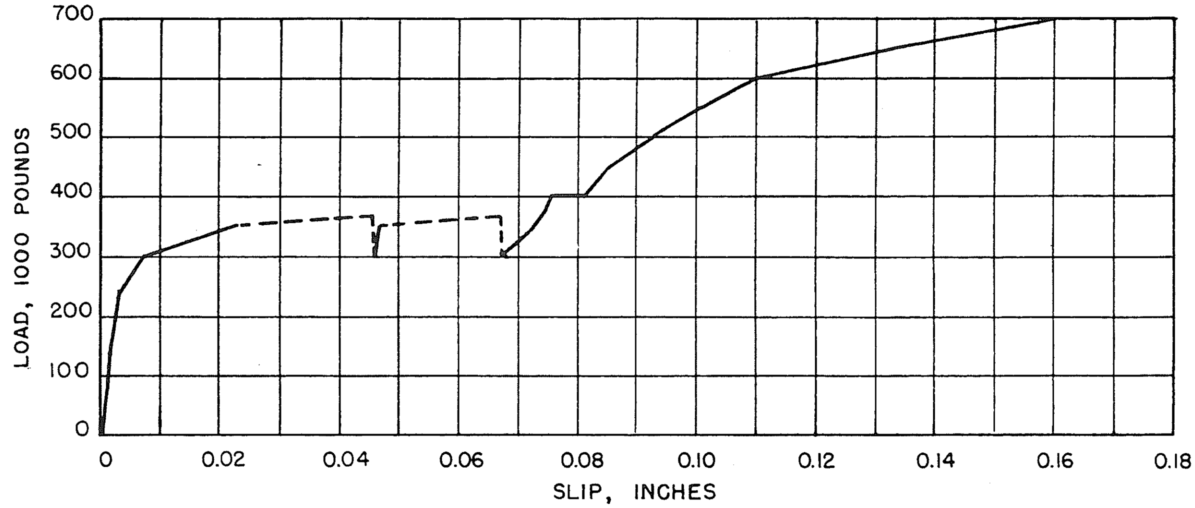
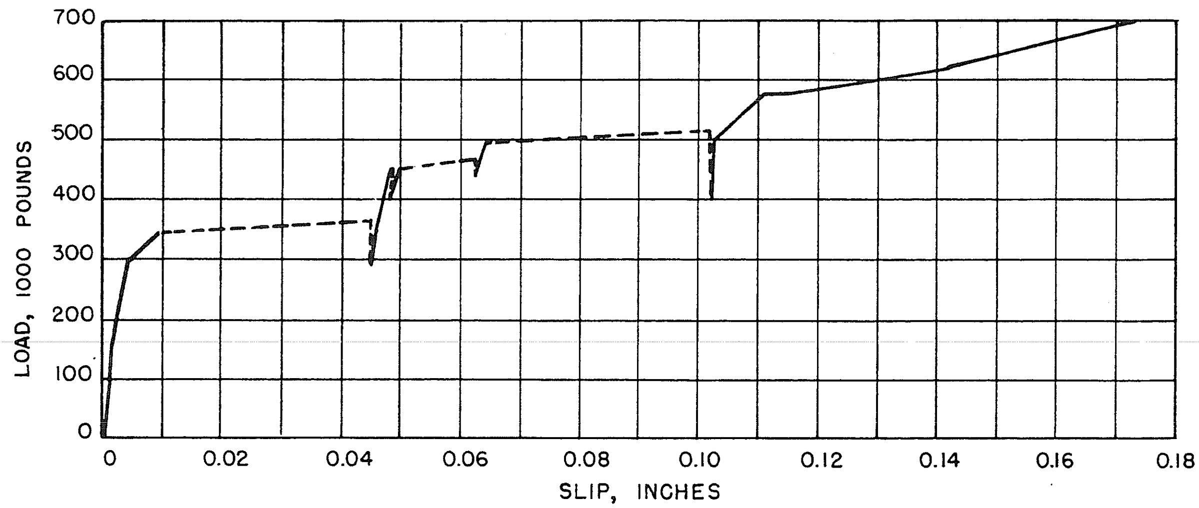


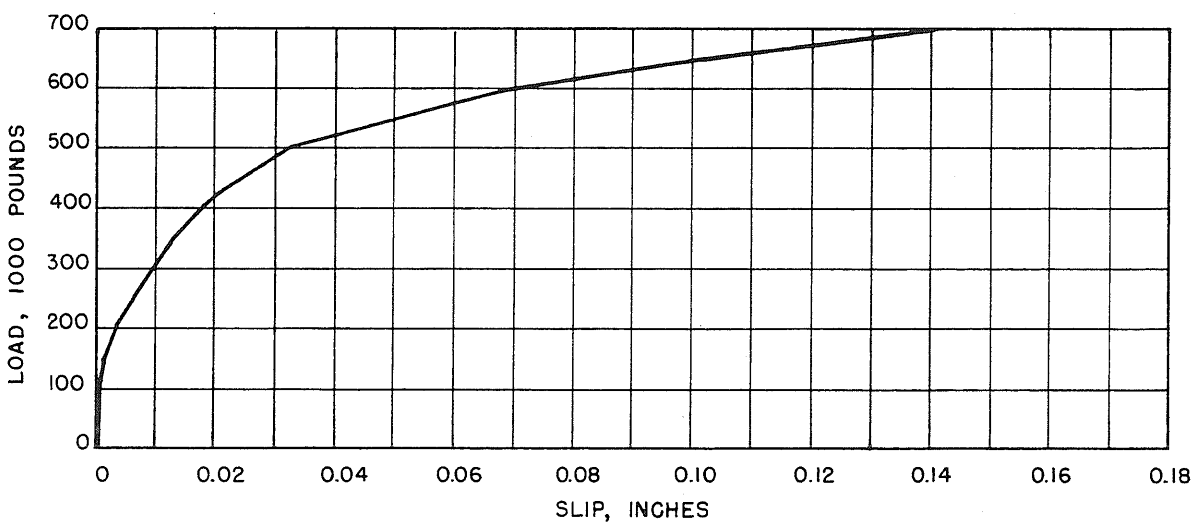
FIG. 15 LOAD-SLIP CURVES FOR SPECIMEN S-3



SPECIMEN S-1 (BEVELED WASHERS)



SPECIMEN S-2 (PLAIN WASHERS)



SPECIMEN S-3 (RIVETED)

FIG. 16 AVERAGE LOAD-SLIP CURVES FOR FIRST ROW FASTENERS OF SPECIMENS S-1, S-2 AND S-3

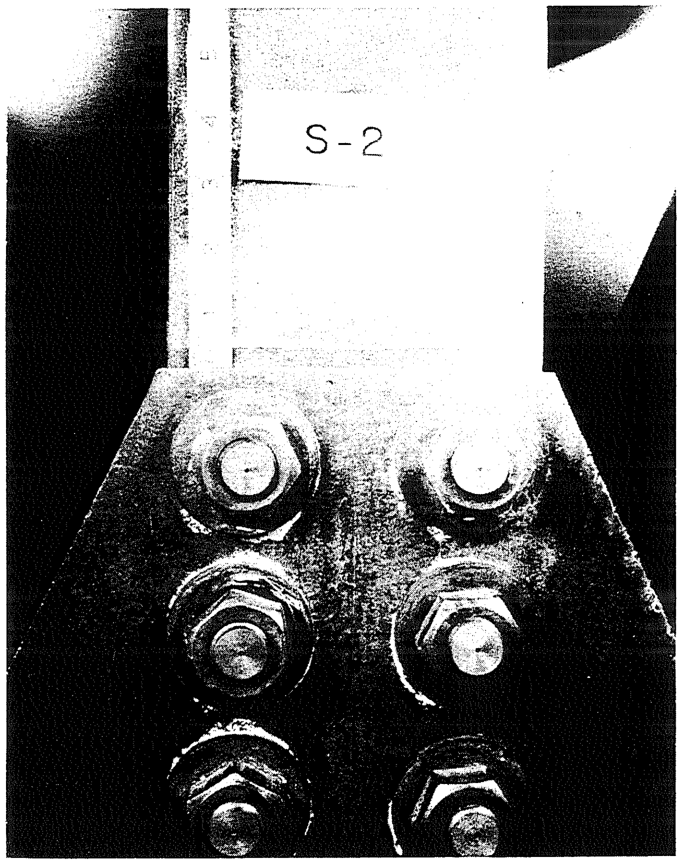


FIG. 17 SLIP AT FAILURE OF SPECIMEN S-2

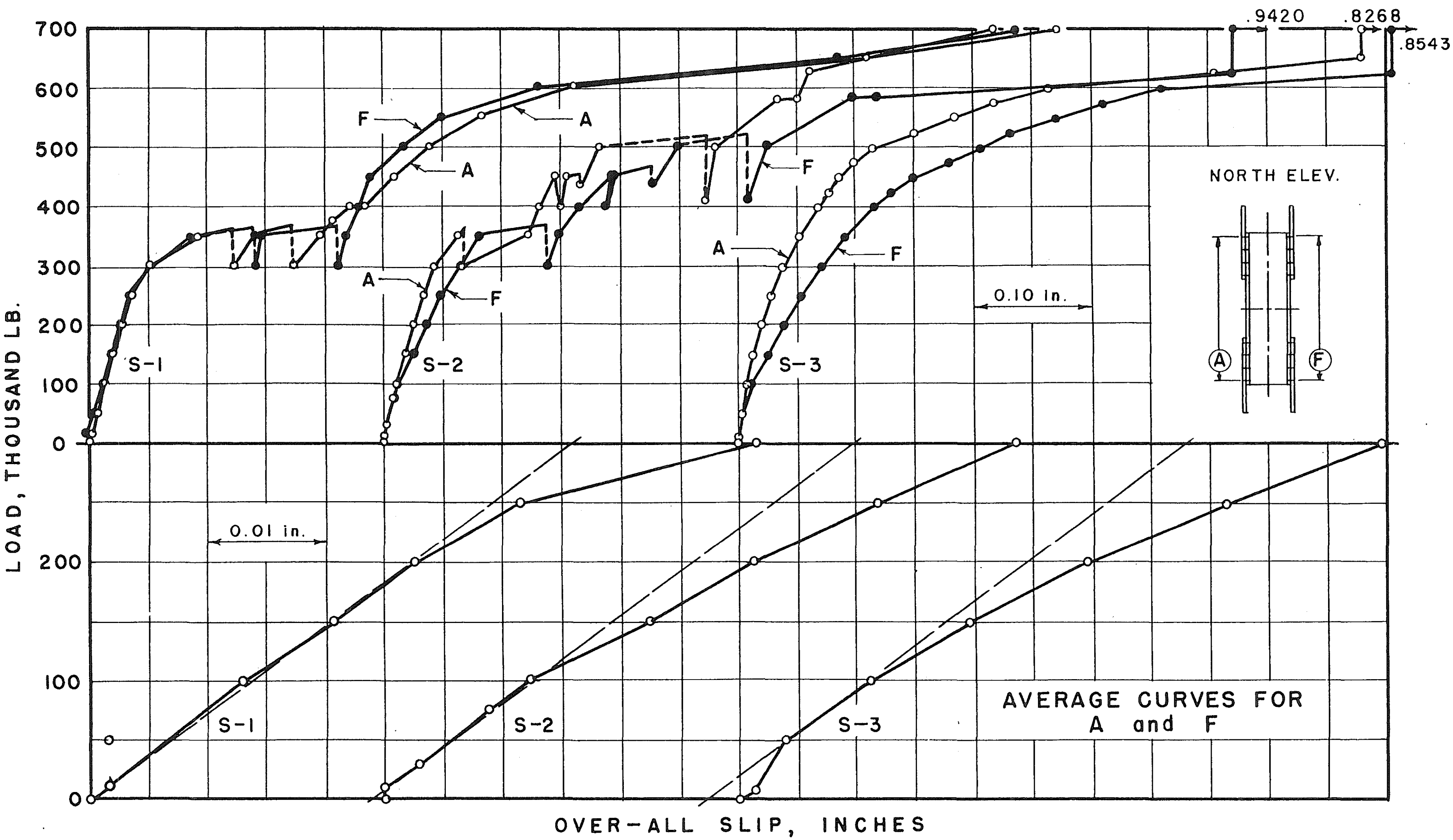


FIG. 18 OVERALL LOAD-SLIP CURVES FOR SPECIMENS S-1, S-2 AND S-3

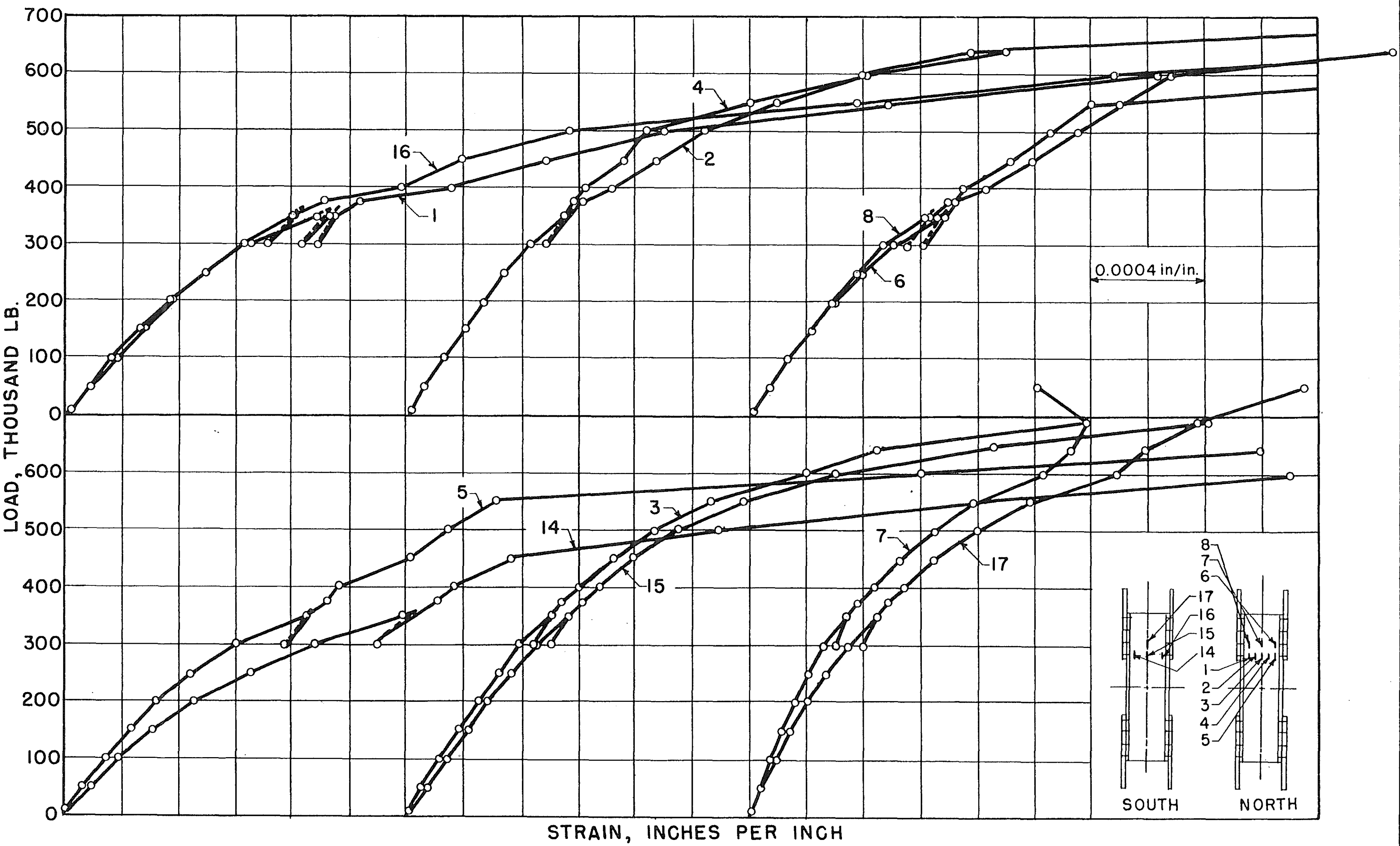


FIG. 19a LOAD-STRAIN RELATIONS AT SR-4 GAGES OF SPECIMEN S-1

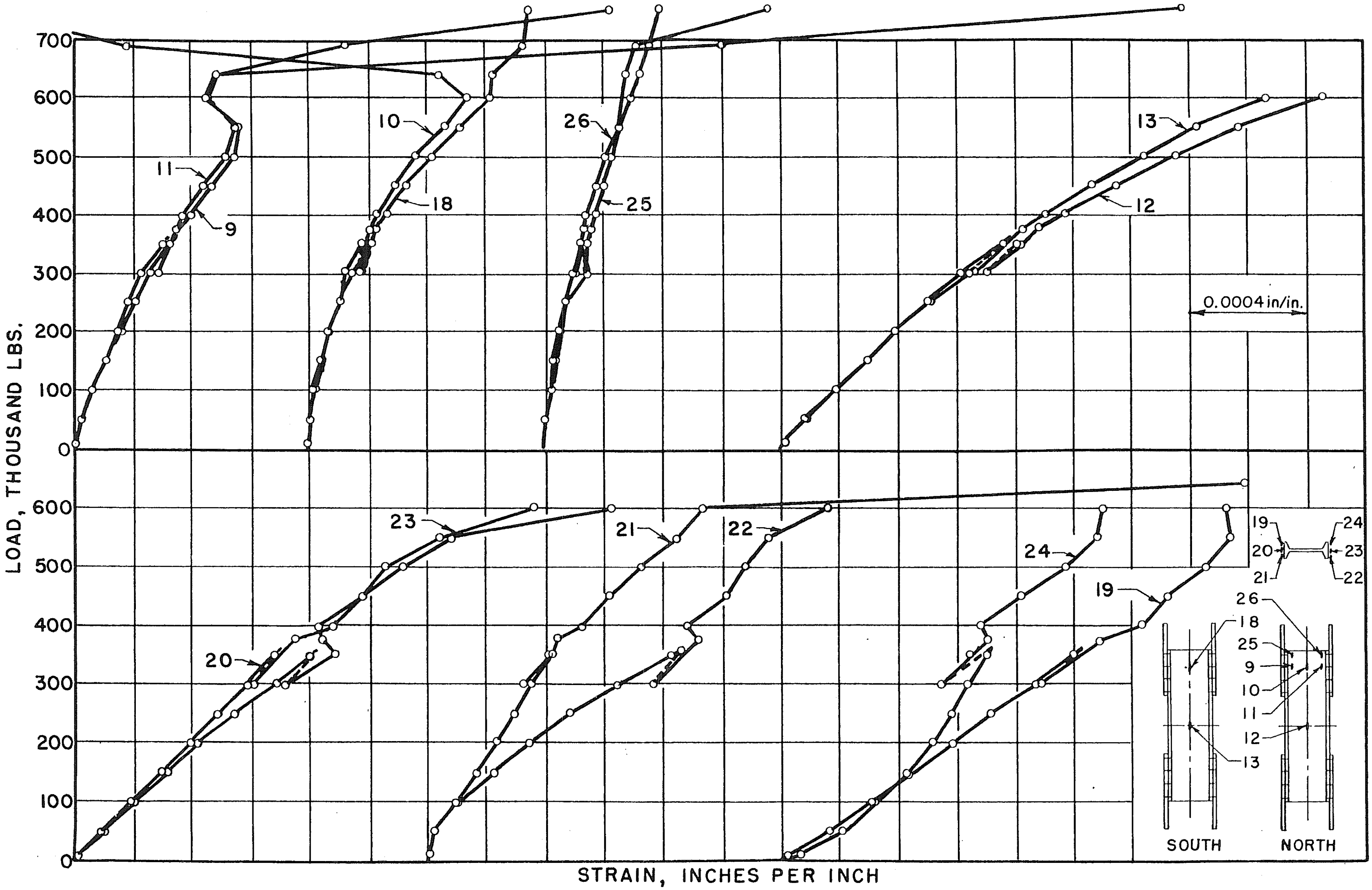


FIG. 19b LOAD-STRAIN RELATIONS AT SR-4 GAGES OF SPECIMEN S-1

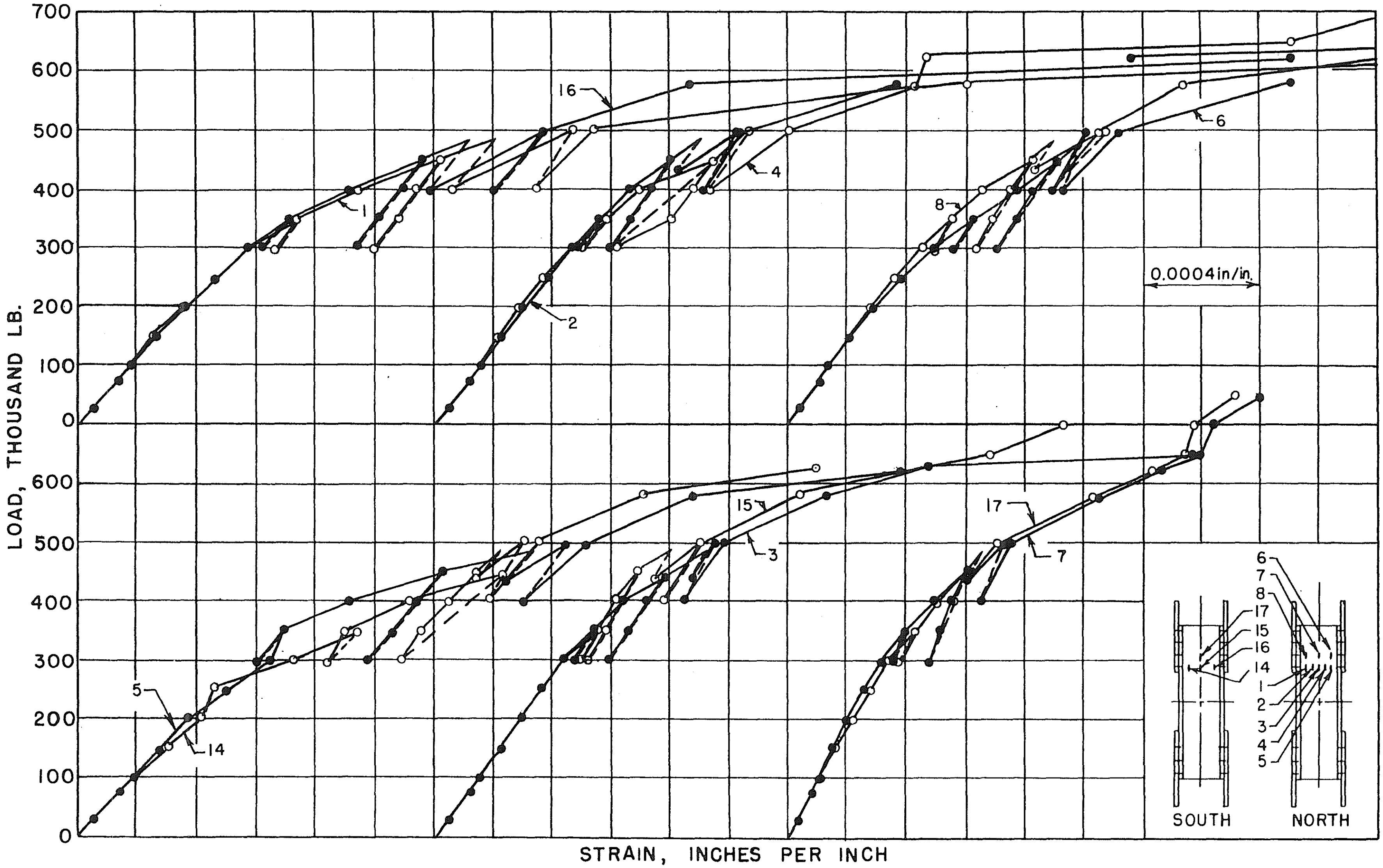


FIG. 20a LOAD-STRAIN RELATIONS AT SR-4 GAGES OF SPECIMEN S-2

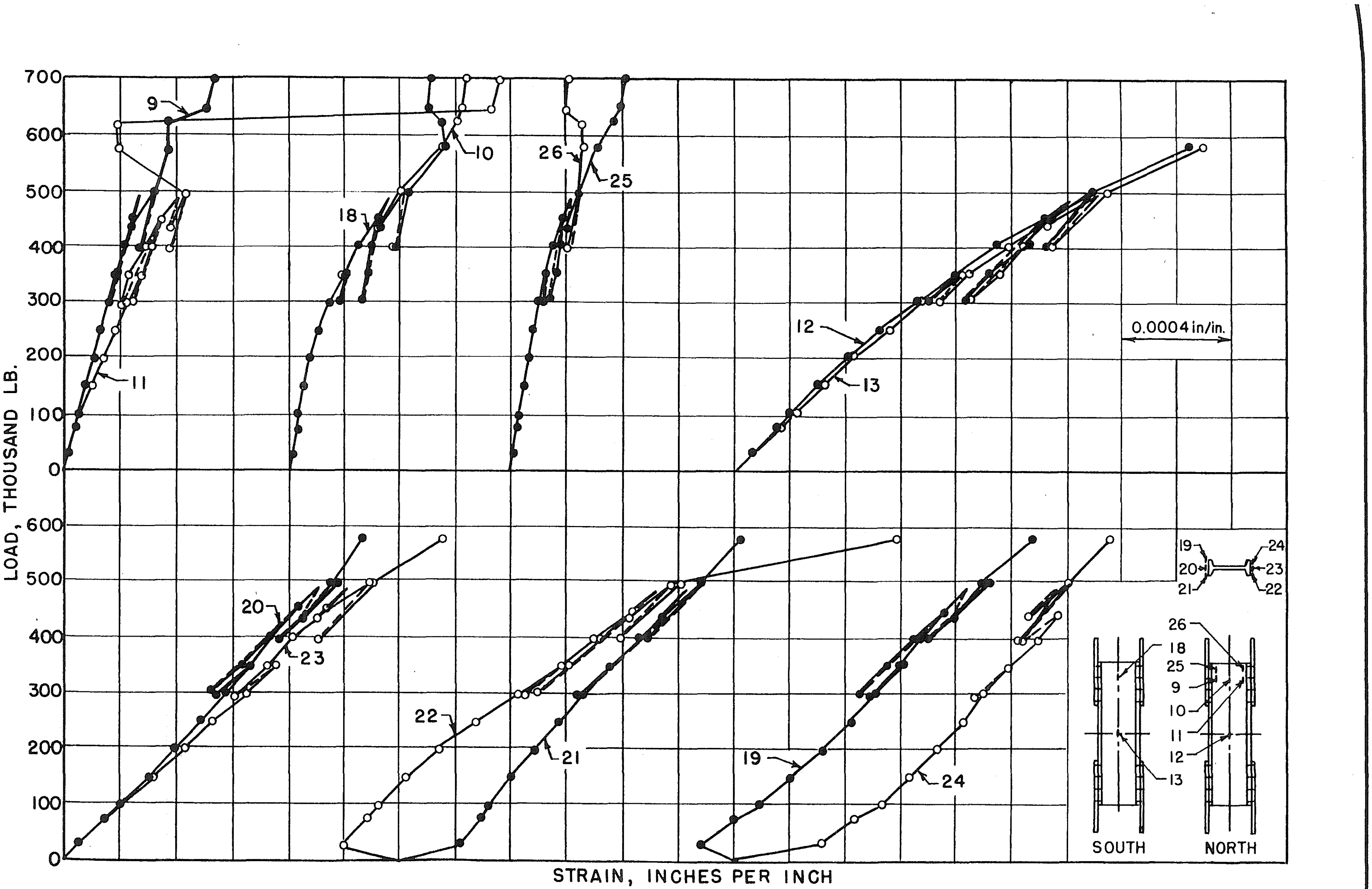


FIG. 20b LOAD-STRAIN RELATIONS AT SR-4 GAGES OF SPECIMEN S-2

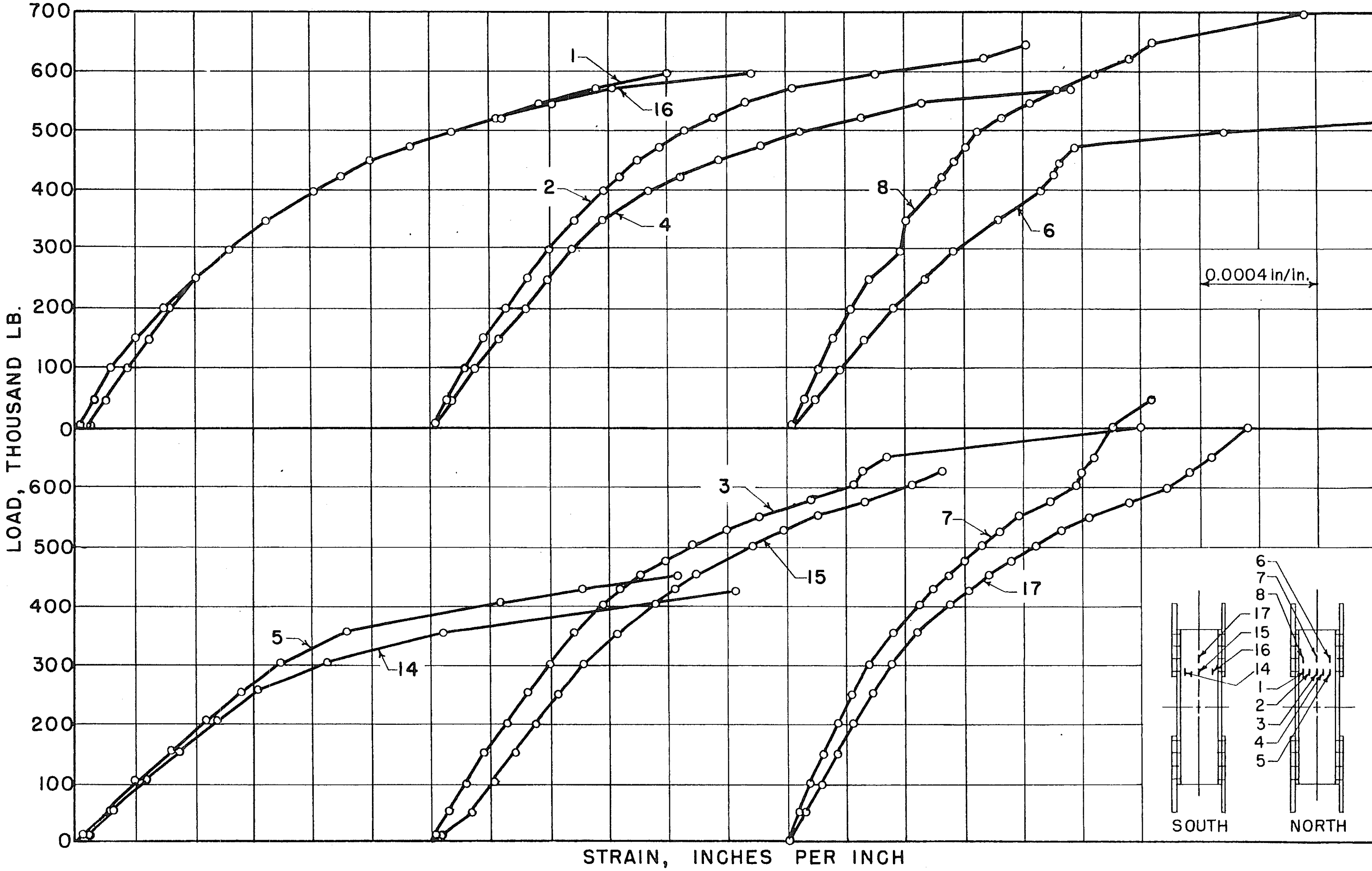


FIG. 21a LOAD-STRAIN RELATIONS AT SR-4 GAGES OF SPECIMEN S-3

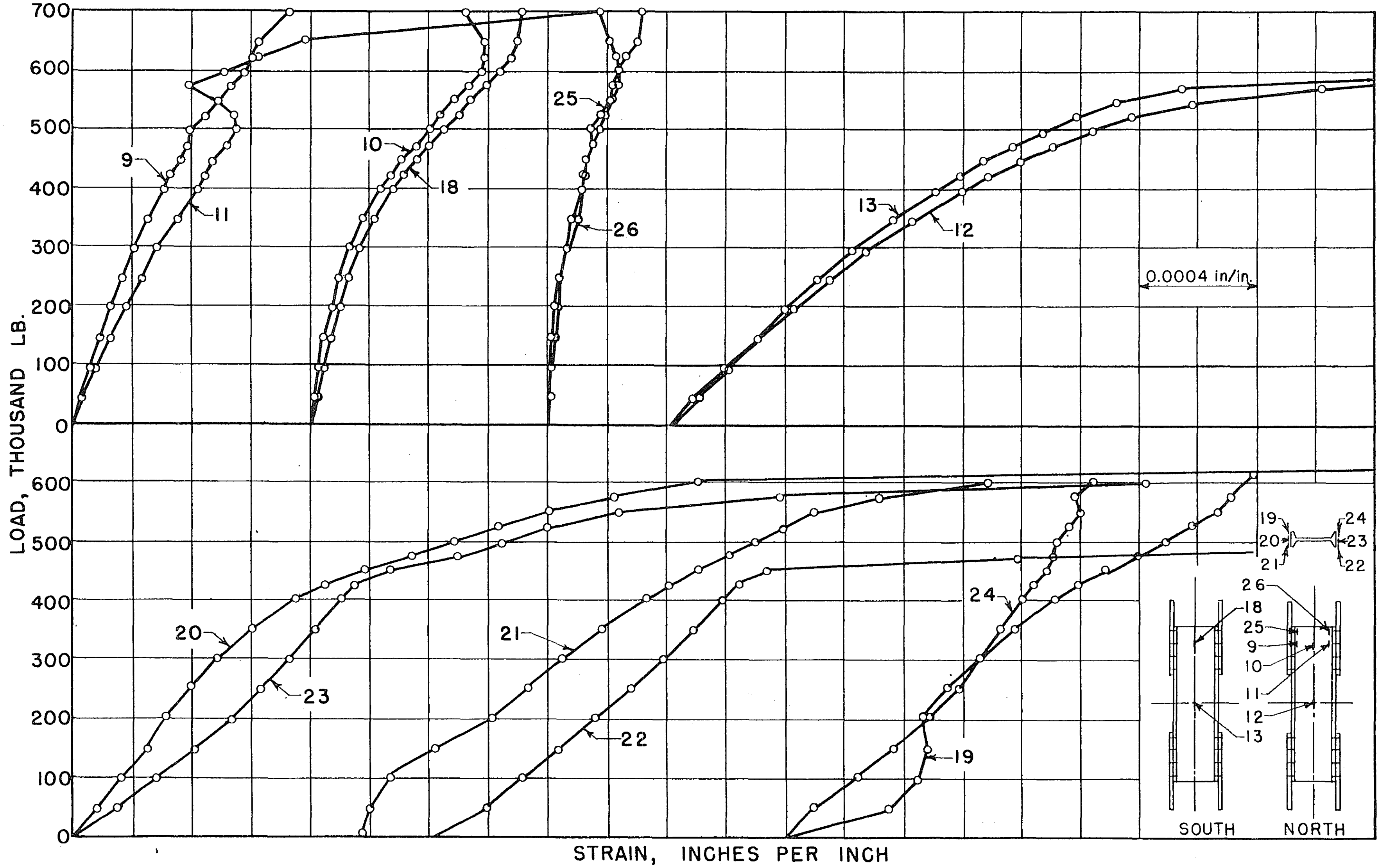


FIG. 21b LOAD-STRAIN RELATIONS AT SR-4 GAGES OF SPECIMEN S-3

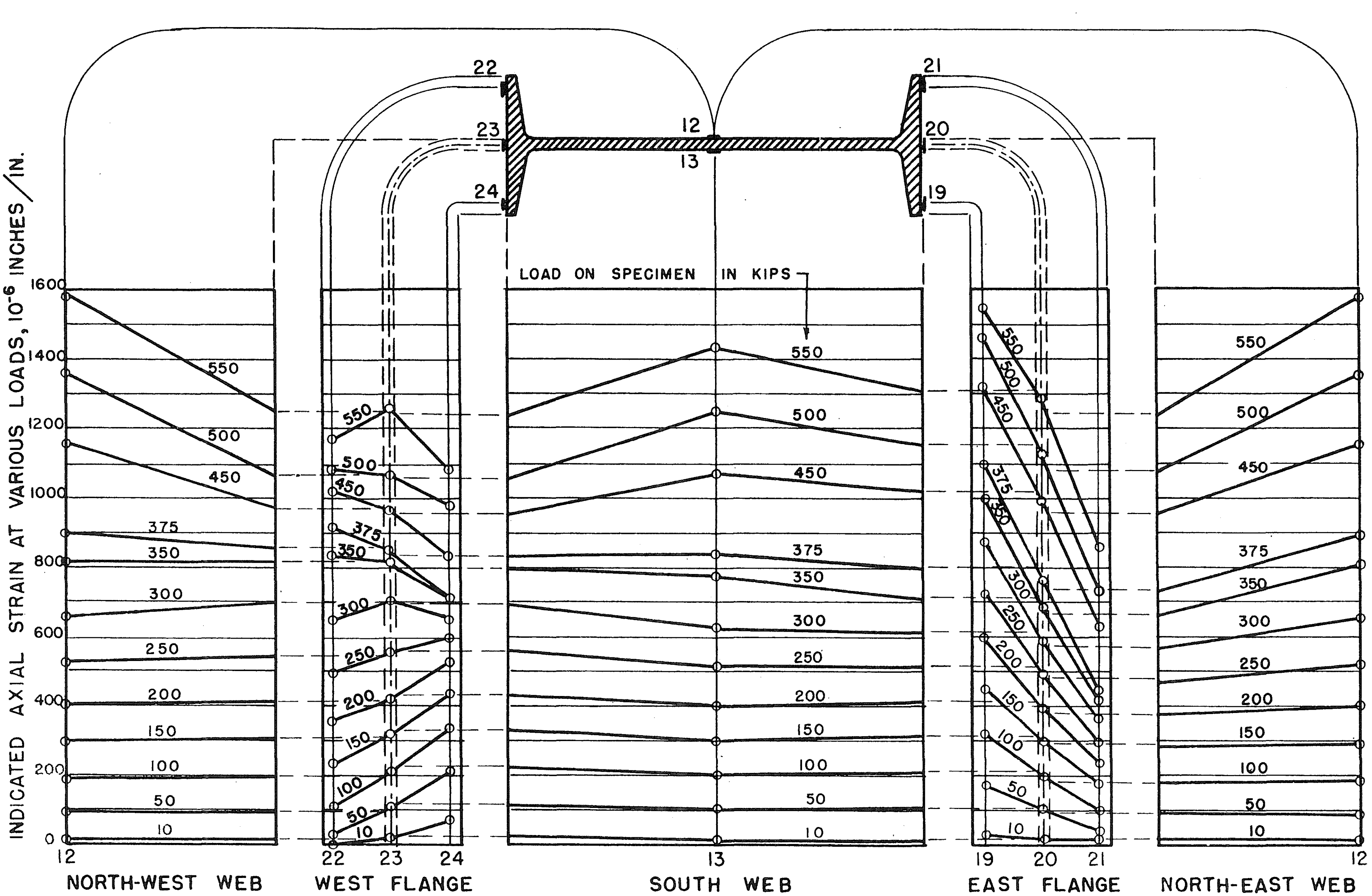


FIG. 22 STRAIN DISTRIBUTION DIAGRAMS FOR CENTER SECTION OF SPECIMEN S-1

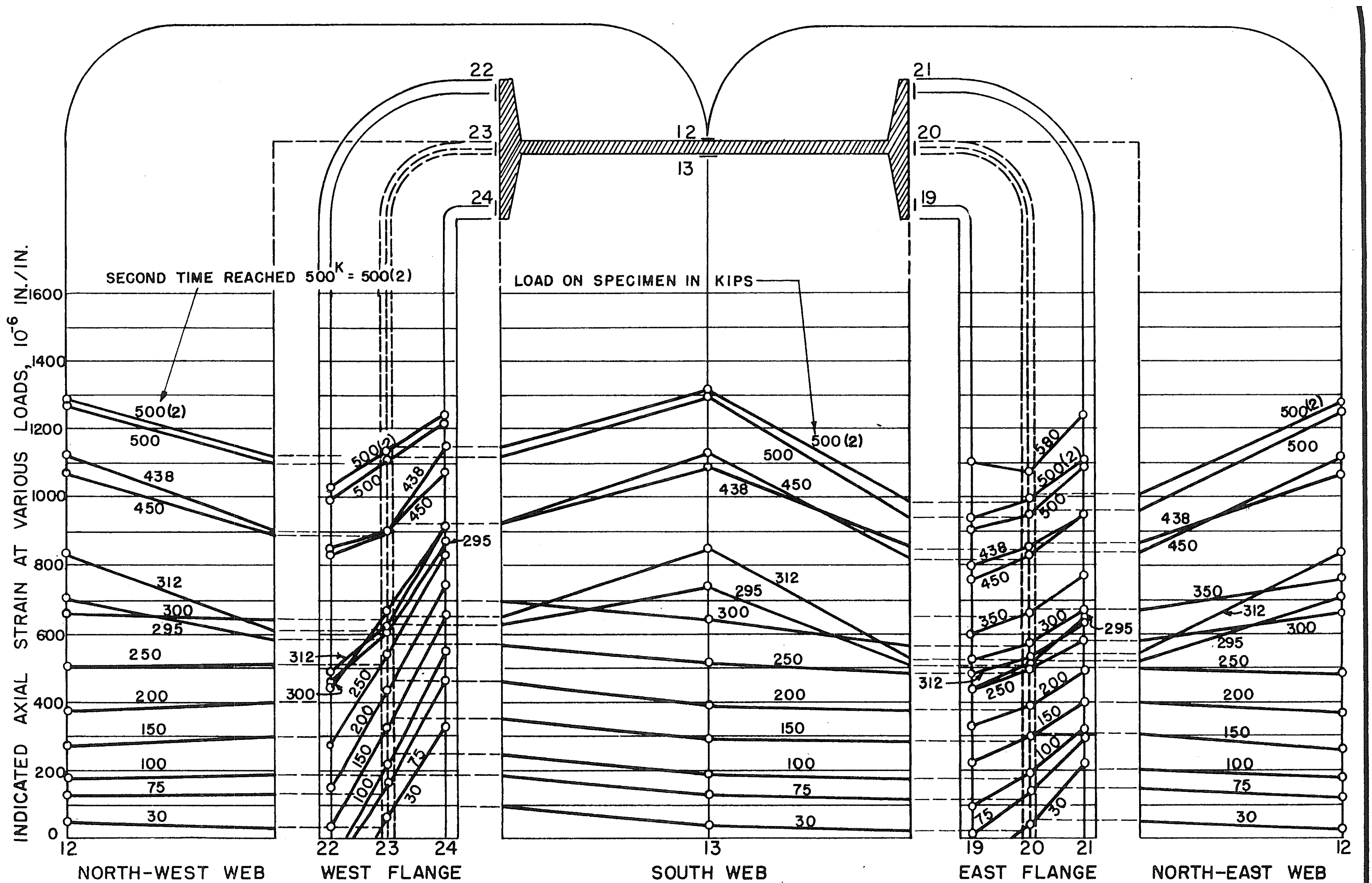


FIG. 23 STRAIN DISTRIBUTION DIAGRAMS FOR CENTER SECTION OF SPECIMEN S-2

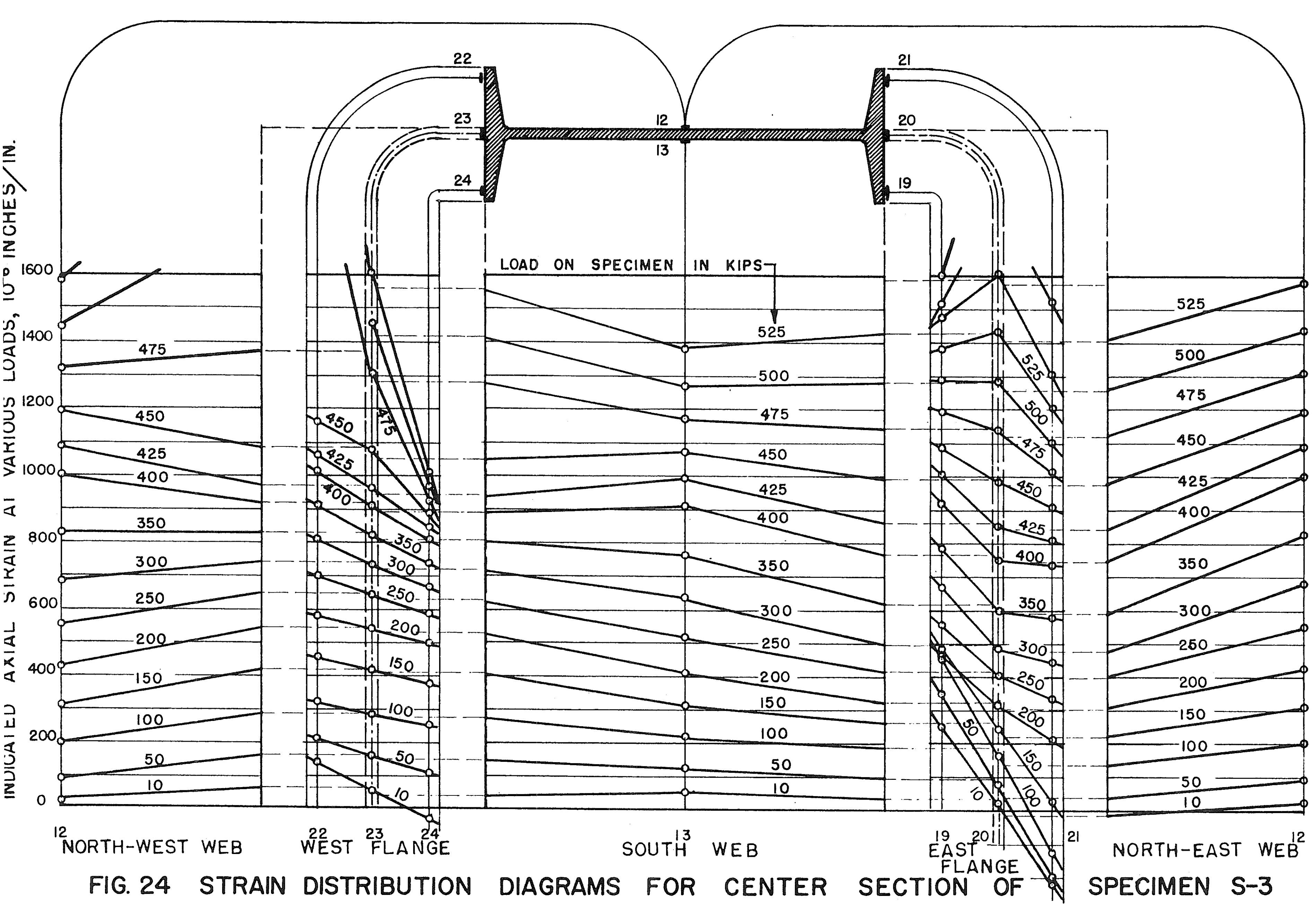


FIG. 24 STRAIN DISTRIBUTION DIAGRAMS FOR CENTER SECTION OF SPECIMEN S-3

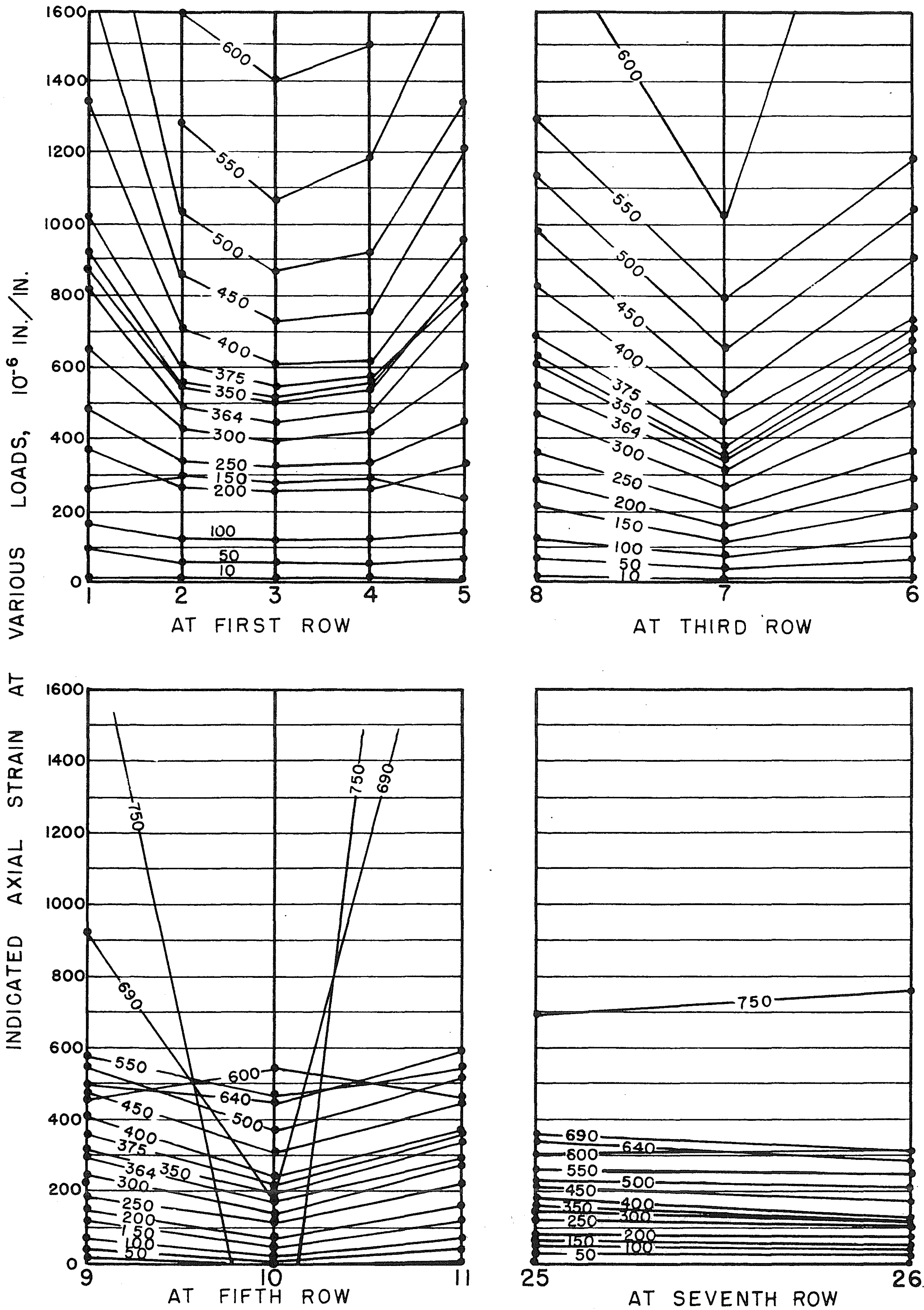


FIG. 25a STRAIN DISTRIBUTION ON HORIZONTAL ROWS OF SR-4 GAGES IN JOINT WEB OF SPECIMEN S-1

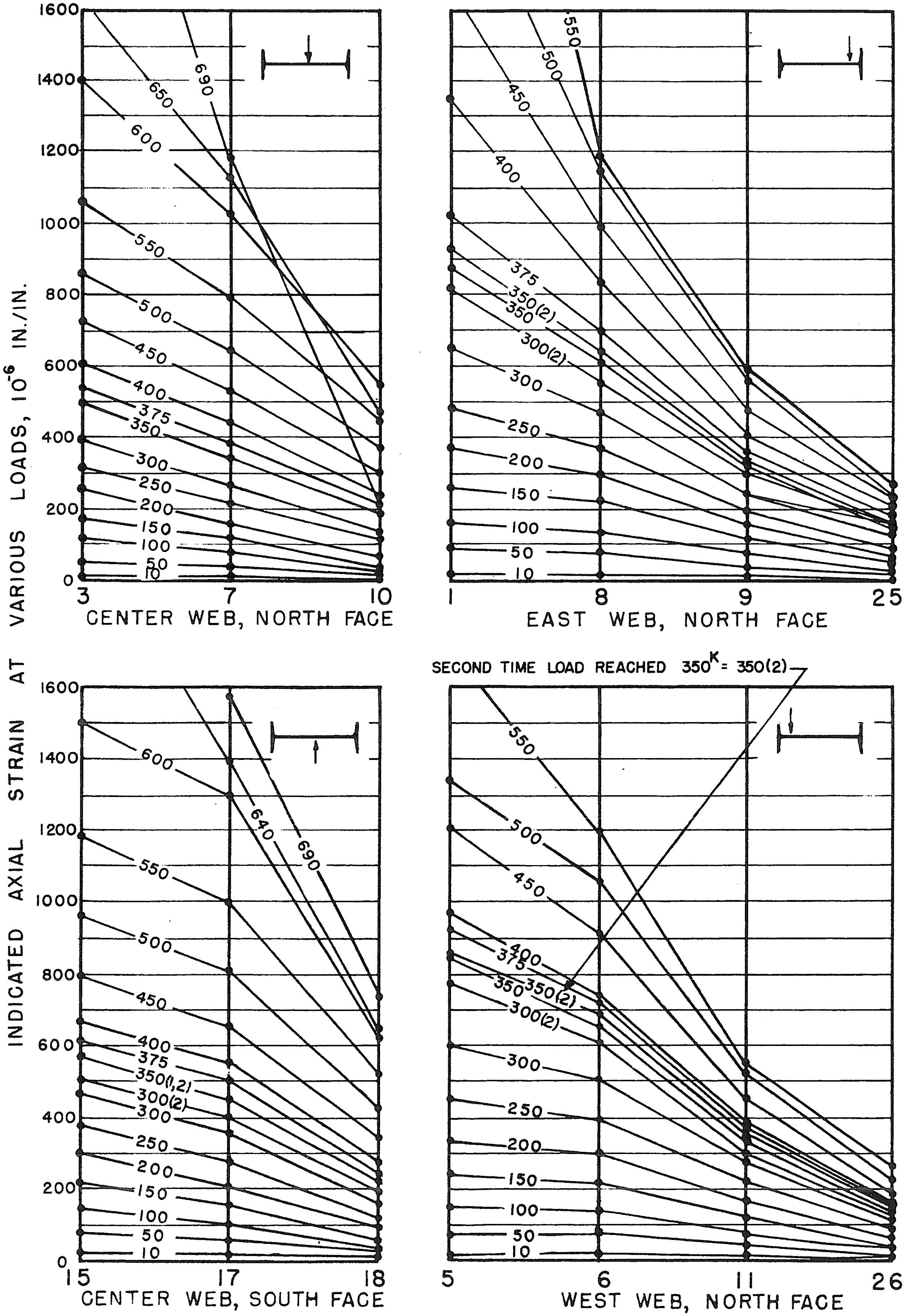


FIG.25b STRAIN DISTRIBUTION ON LONGITUDINAL LINES OF SR-4 GAGES IN JOINT WEB OF SPECIMEN S-1

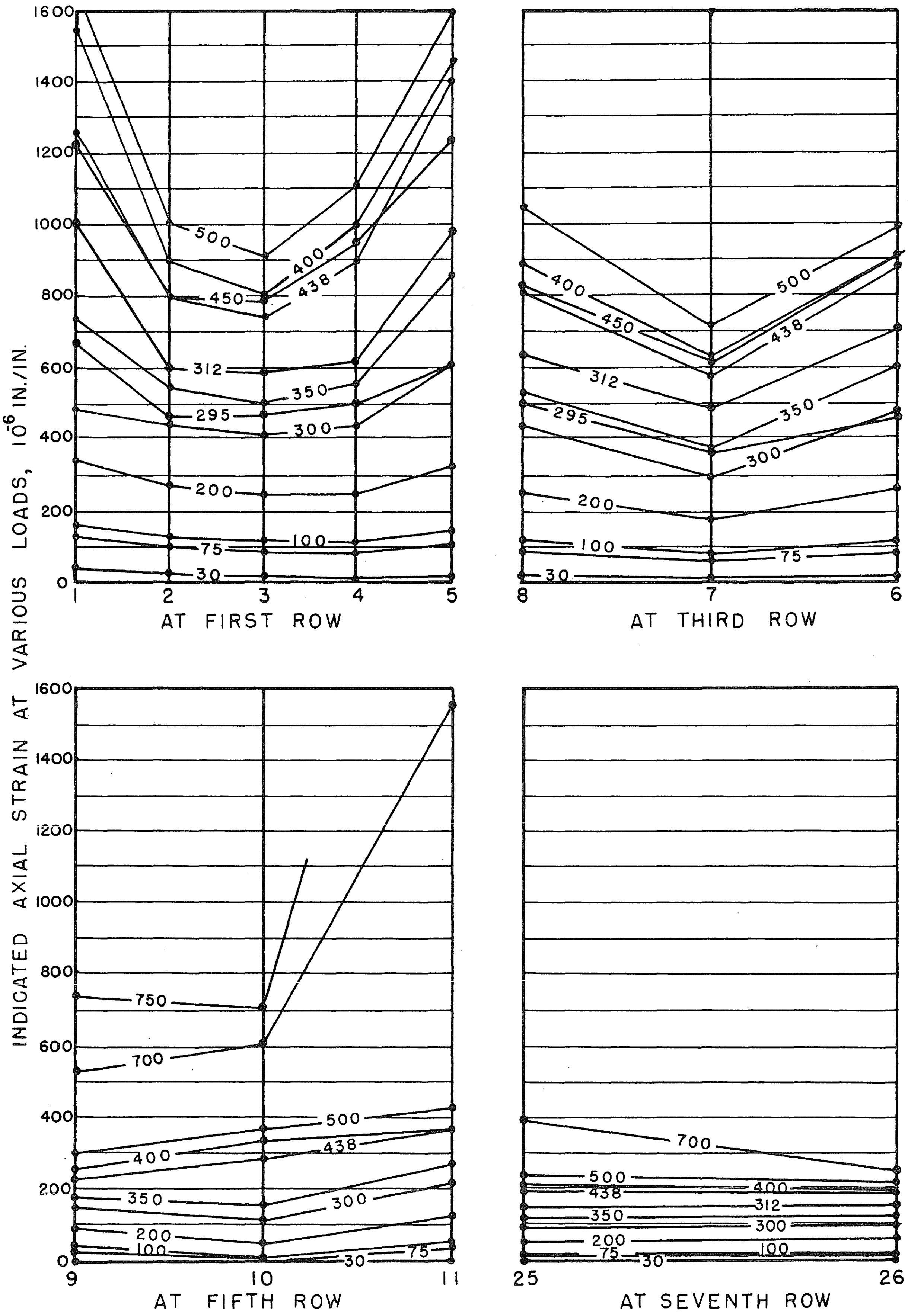


FIG. 26a STRAIN DISTRIBUTION ON HORIZONTAL ROWS OF SR-4 GAGES IN JOINT WEB OF SPECIMEN S-2

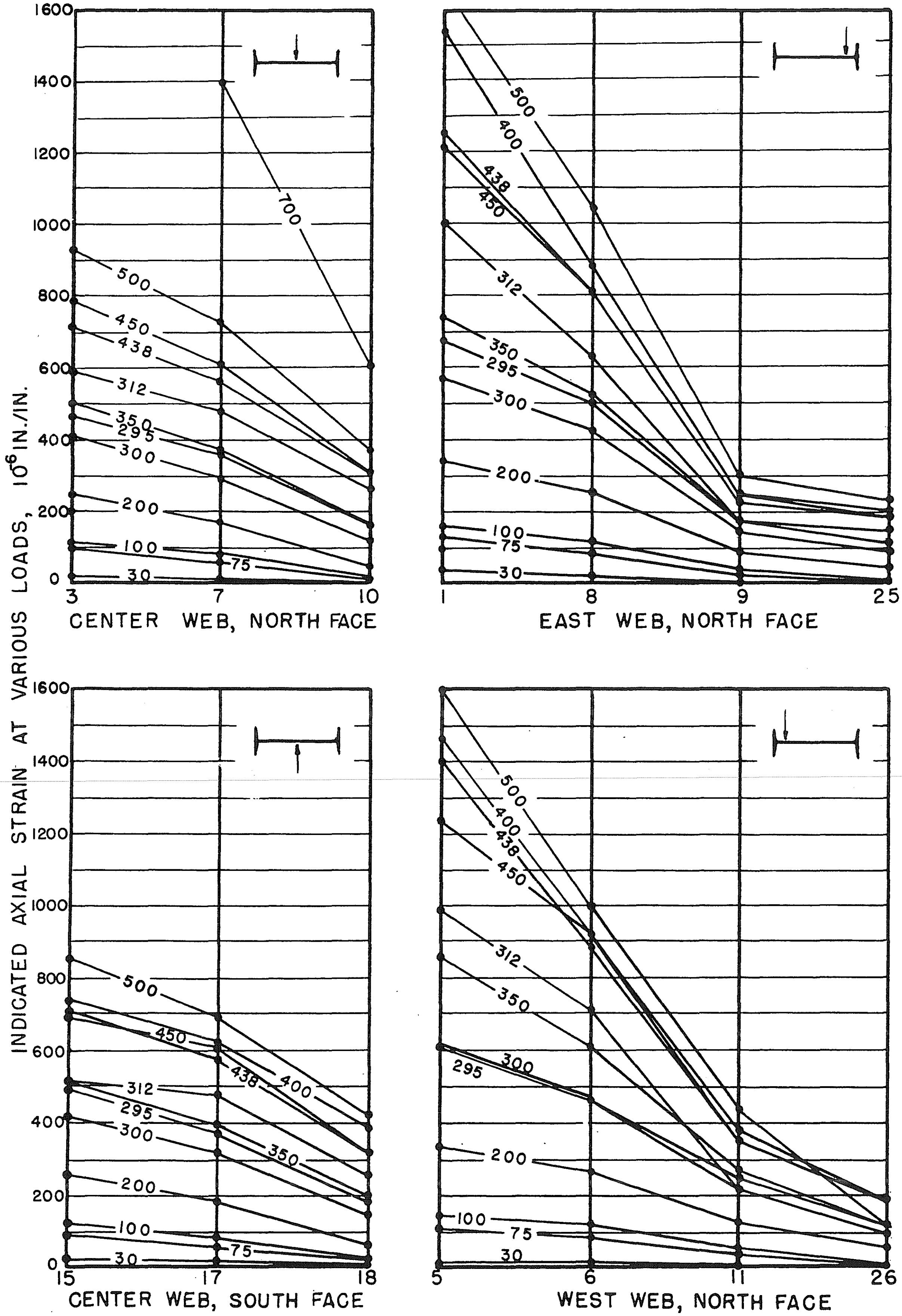


FIG. 26b STRAIN DISTRIBUTION ON LONGITUDINAL LINES OF SR-4 GAGES IN JOINT WEB OF SPECIMEN S-2

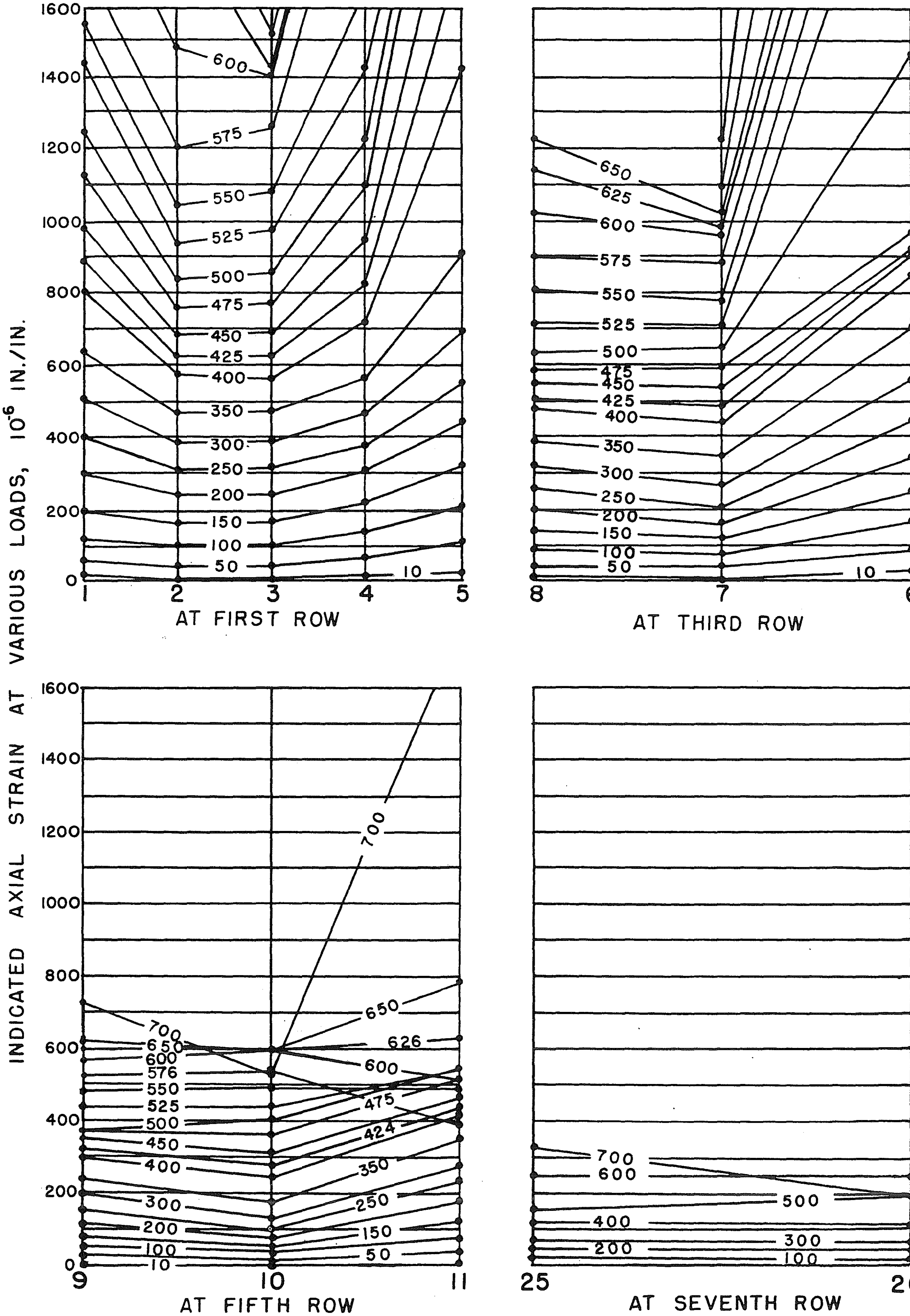


FIG. 27a STRAIN DISTRIBUTION ON HORIZONTAL ROWS OF SR-4 GAGES IN JOINT WEB OF SPECIMEN S-3

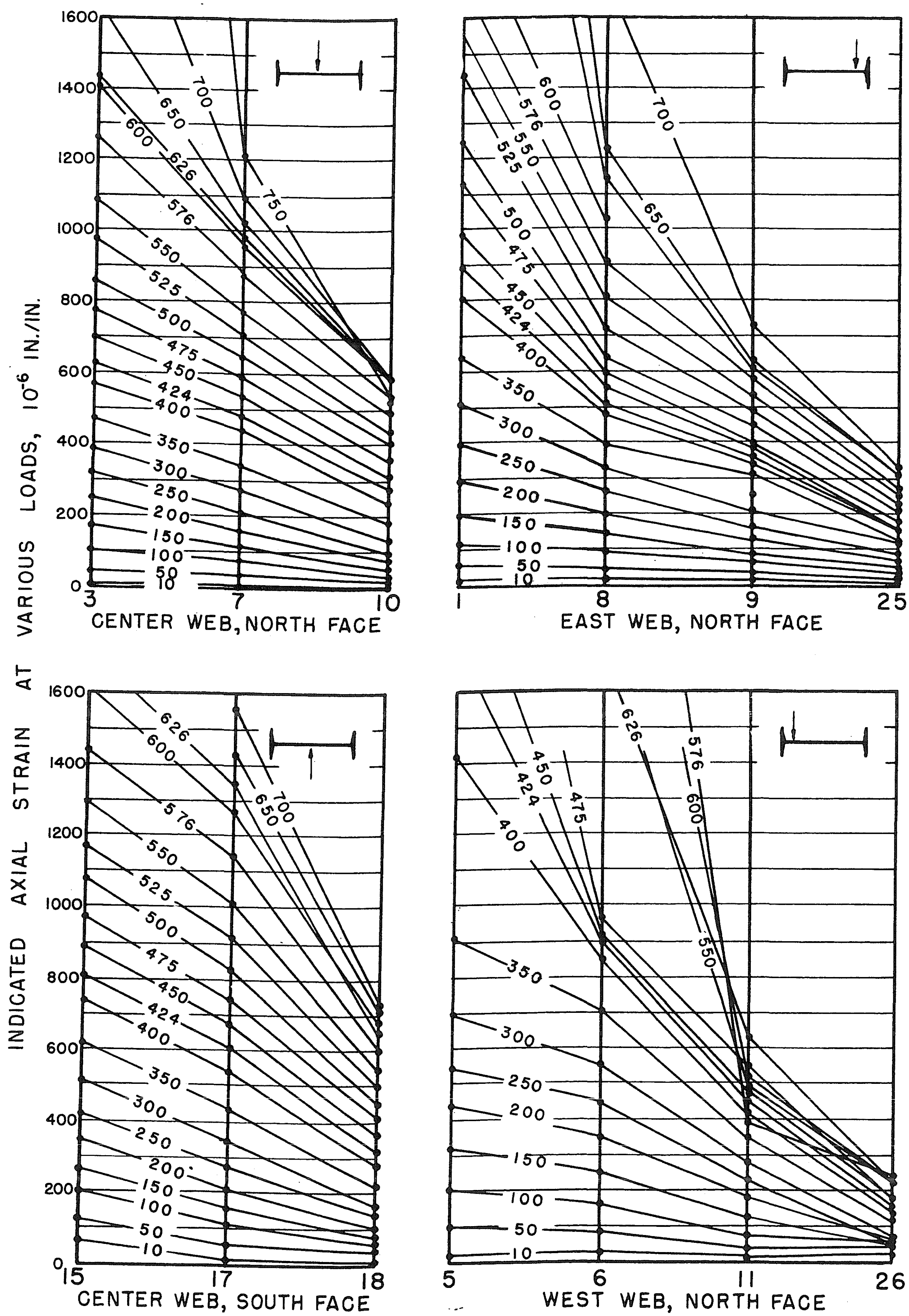


FIG. 27b STRAIN DISTRIBUTION ON LONGITUDINAL LINES OF SR-4 GAGES IN JOINT WEB OF SPECIMEN S-3

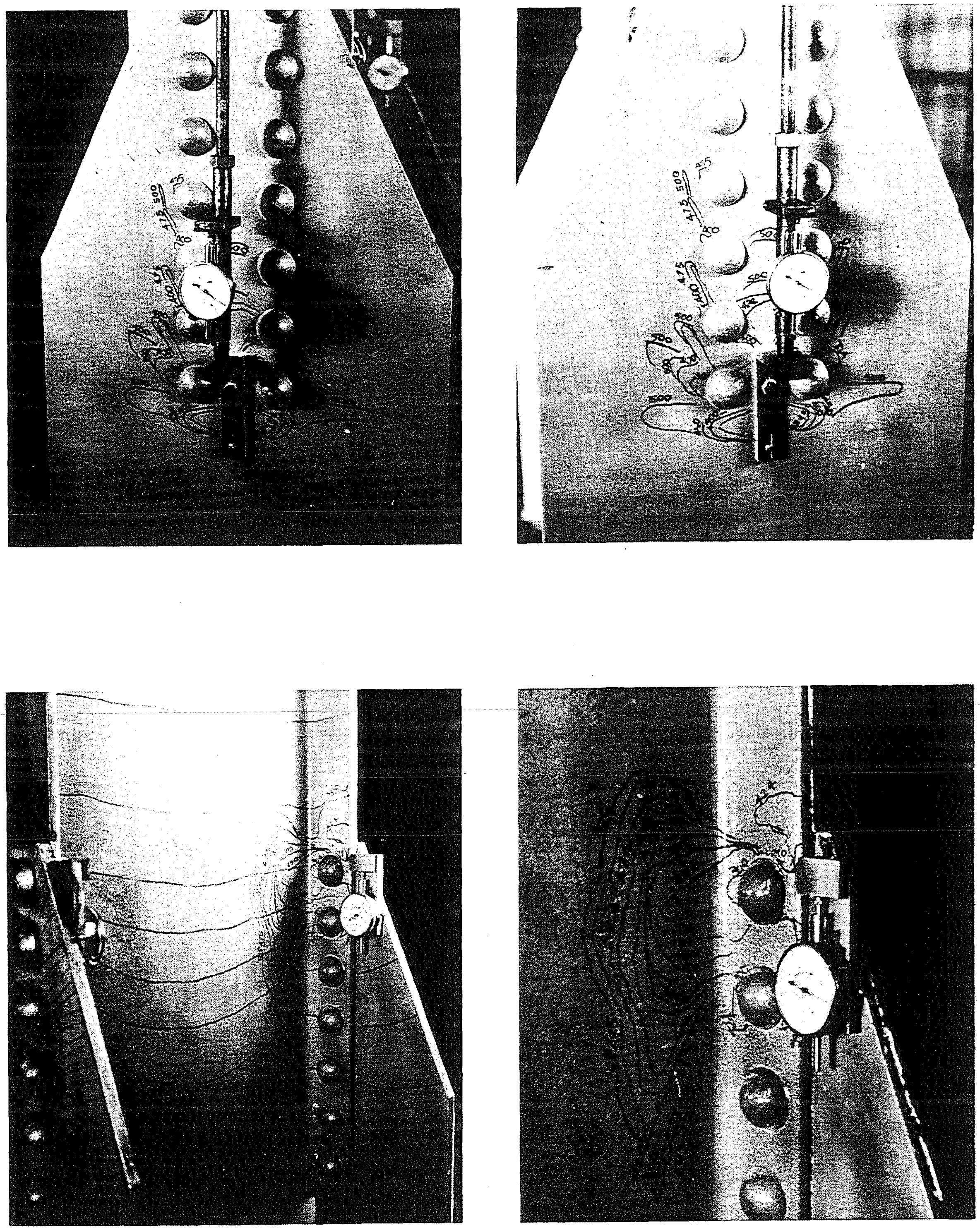
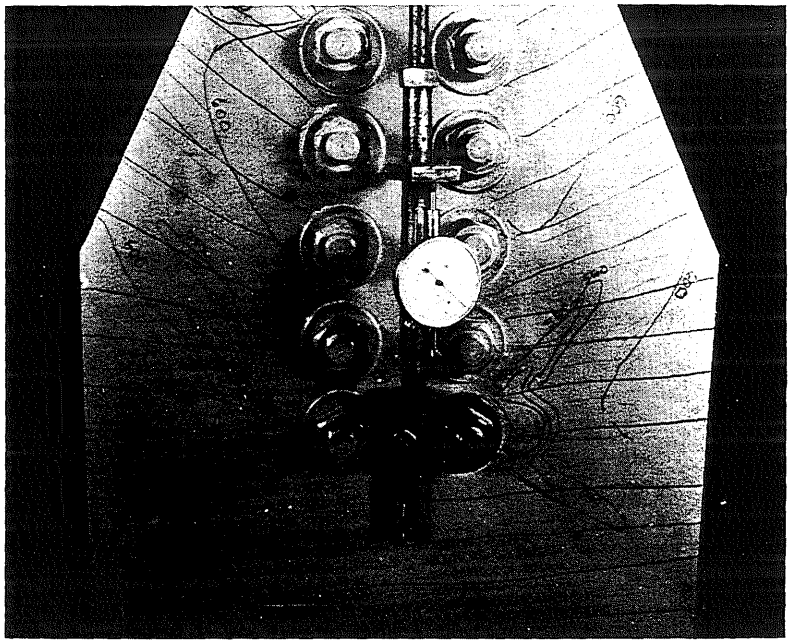
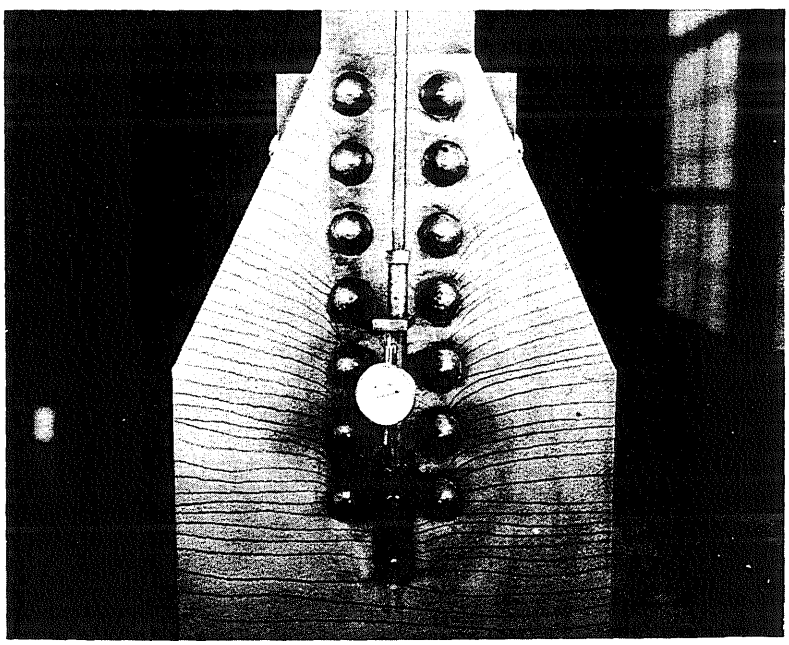


FIG. 28 BRITTLE LACQUER CRACK PATTERNS ON GUSSET PLATE AND I-BEAM OF SPECIMEN S-3



SPECIMEN S-1



SPECIMEN S-3

FIG. 29 BRITTLE LACQUER CRACK PATTERNS ON GUSSET PLATES OF SPECIMENS S-1 AND S-3

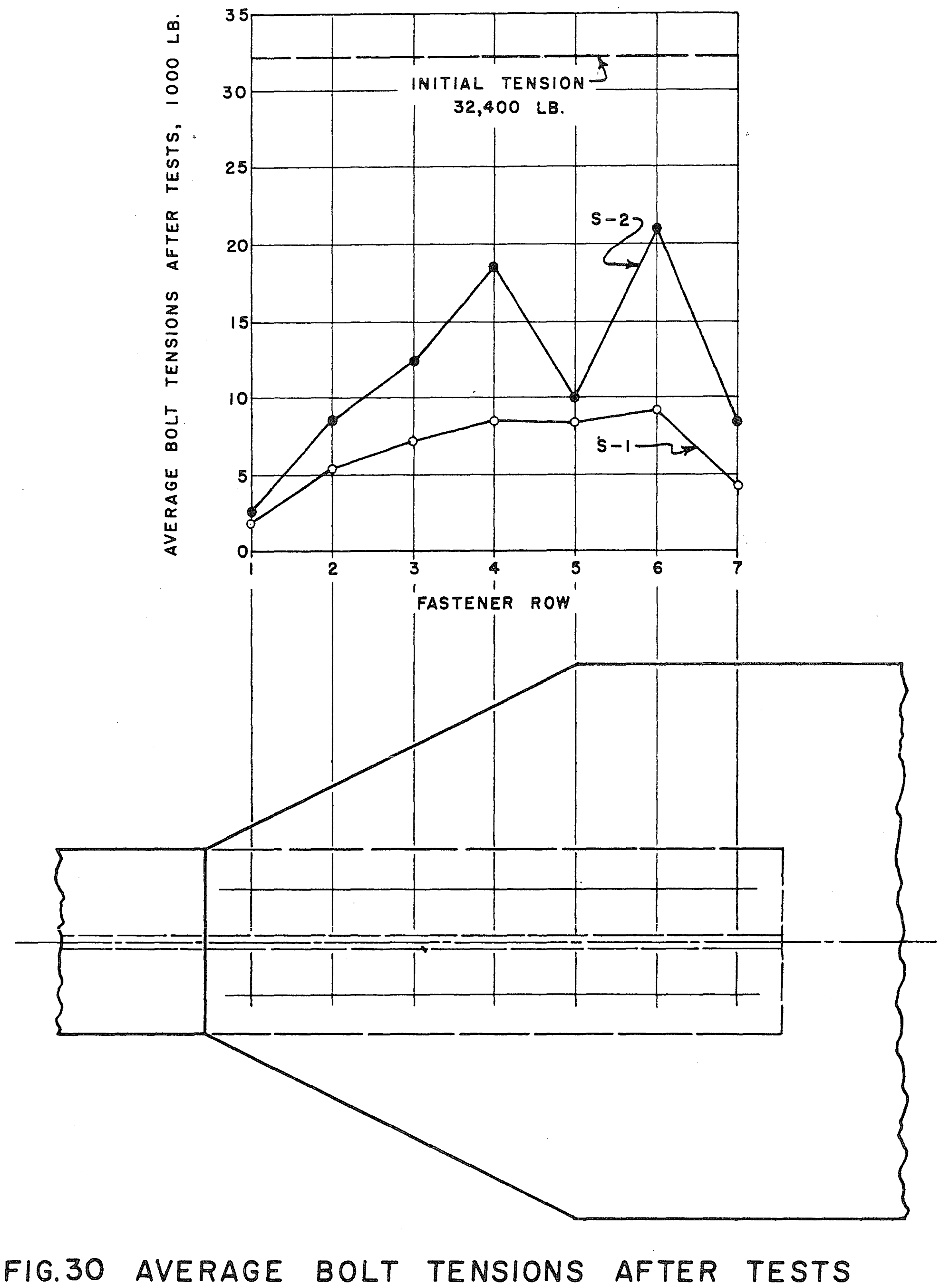


FIG.30 AVERAGE BOLT TENSIONS AFTER TESTS

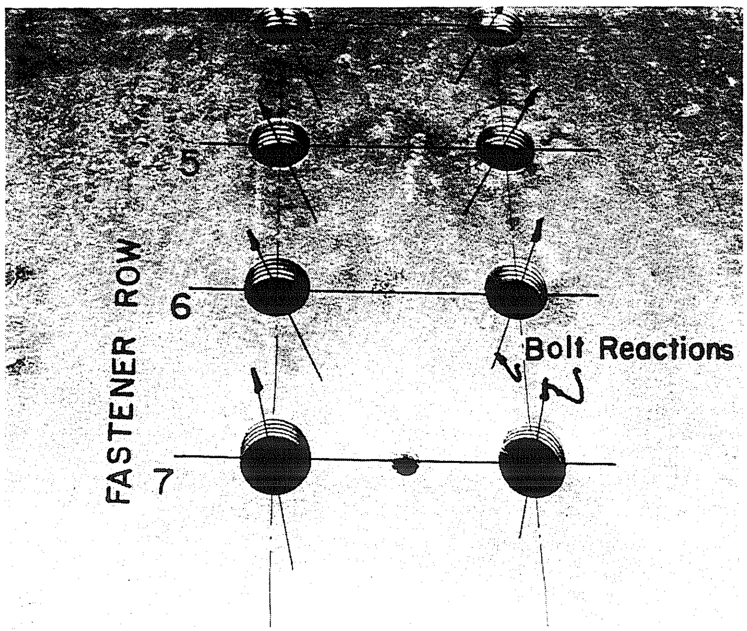


FIG. 31 SPECIMEN S-2 GUSSET AT LAST ROW OF FASTENERS

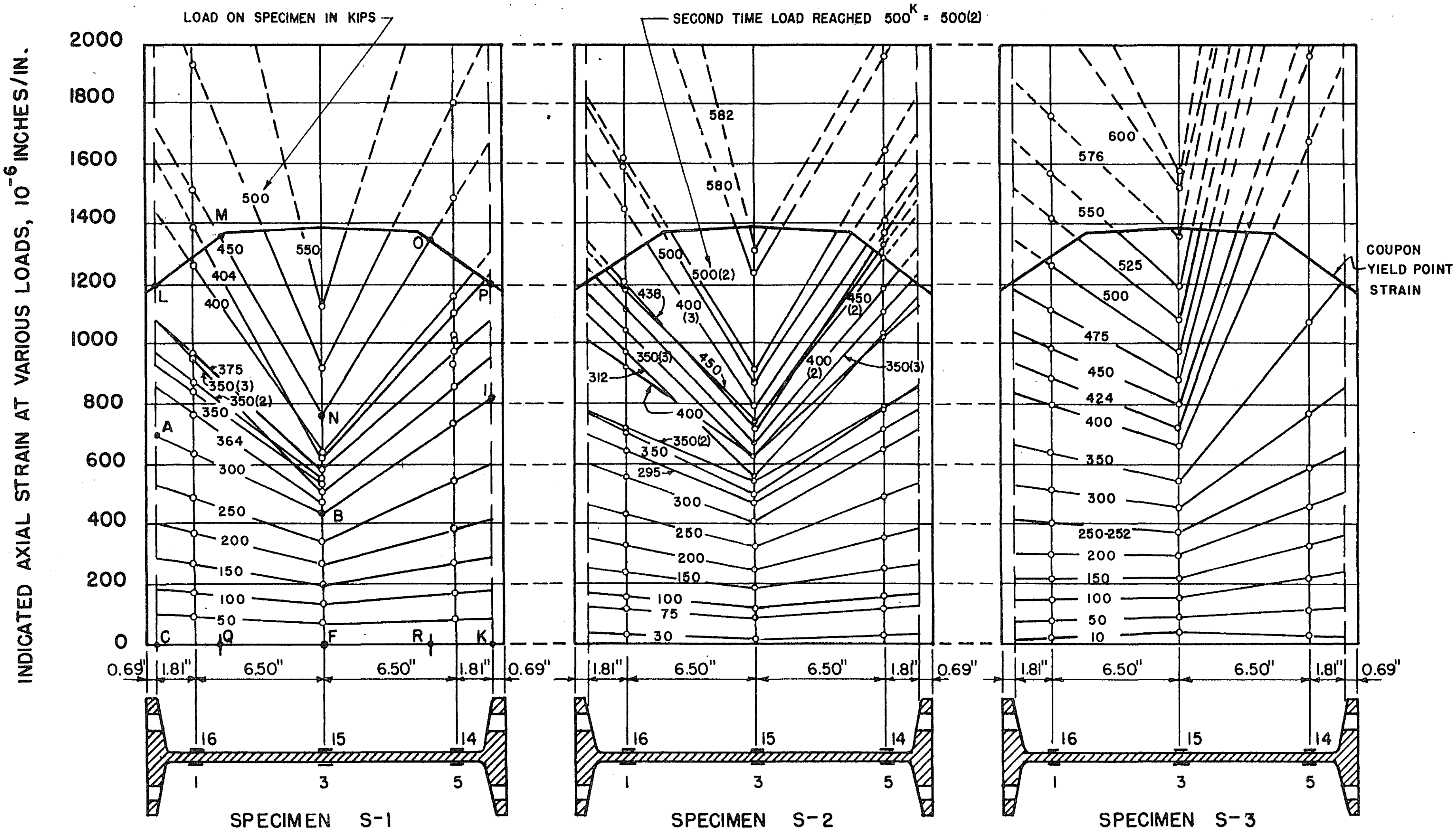


FIG.32 AVERAGE STRAIN DISTRIBUTION IN WEBS AT FIRST ROW FASTENERS

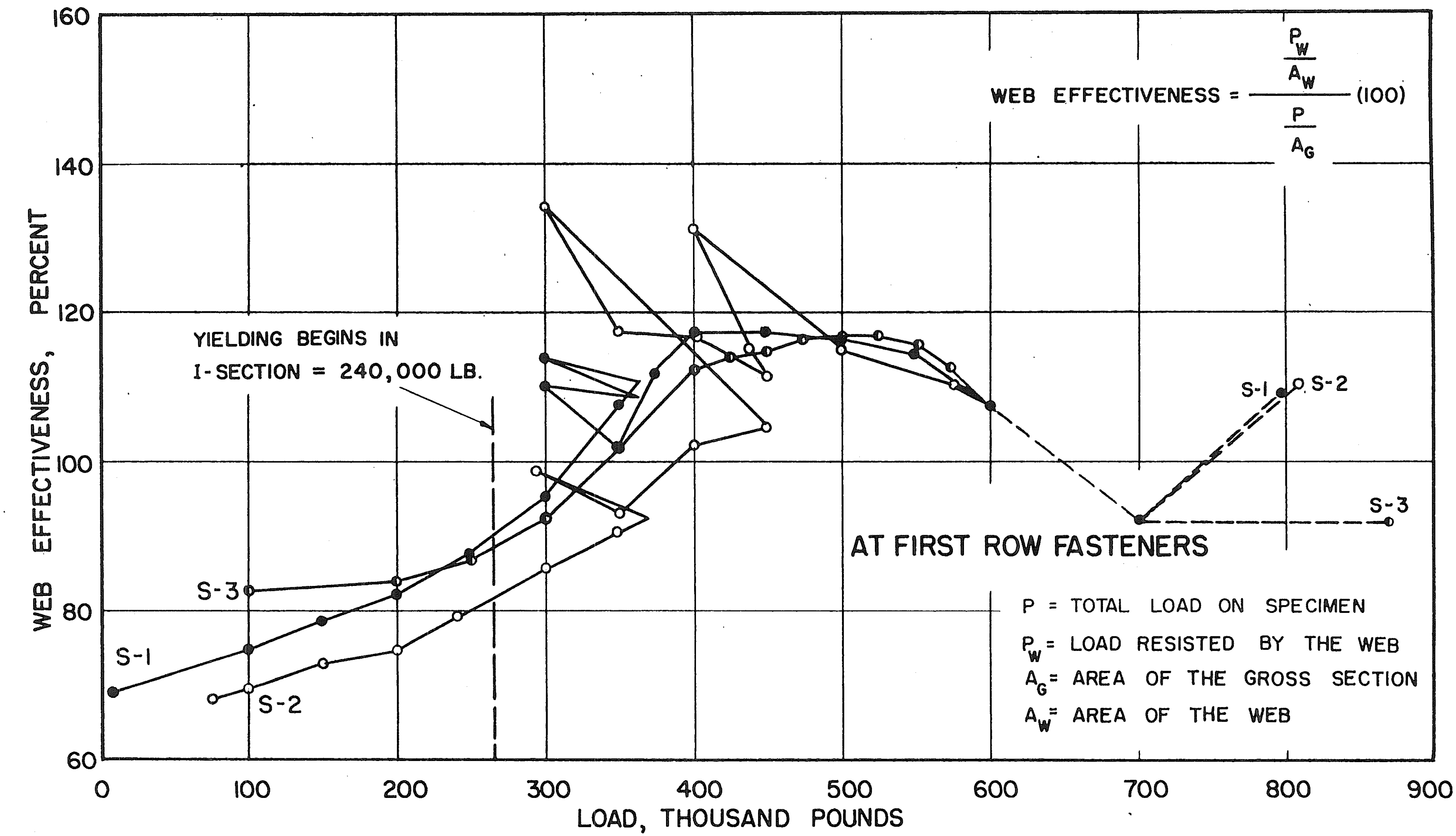


FIG. 33 WEB EFFECTIVENESS DIAGRAM FOR SPECIMENS S-1, S-2, AND S-3.

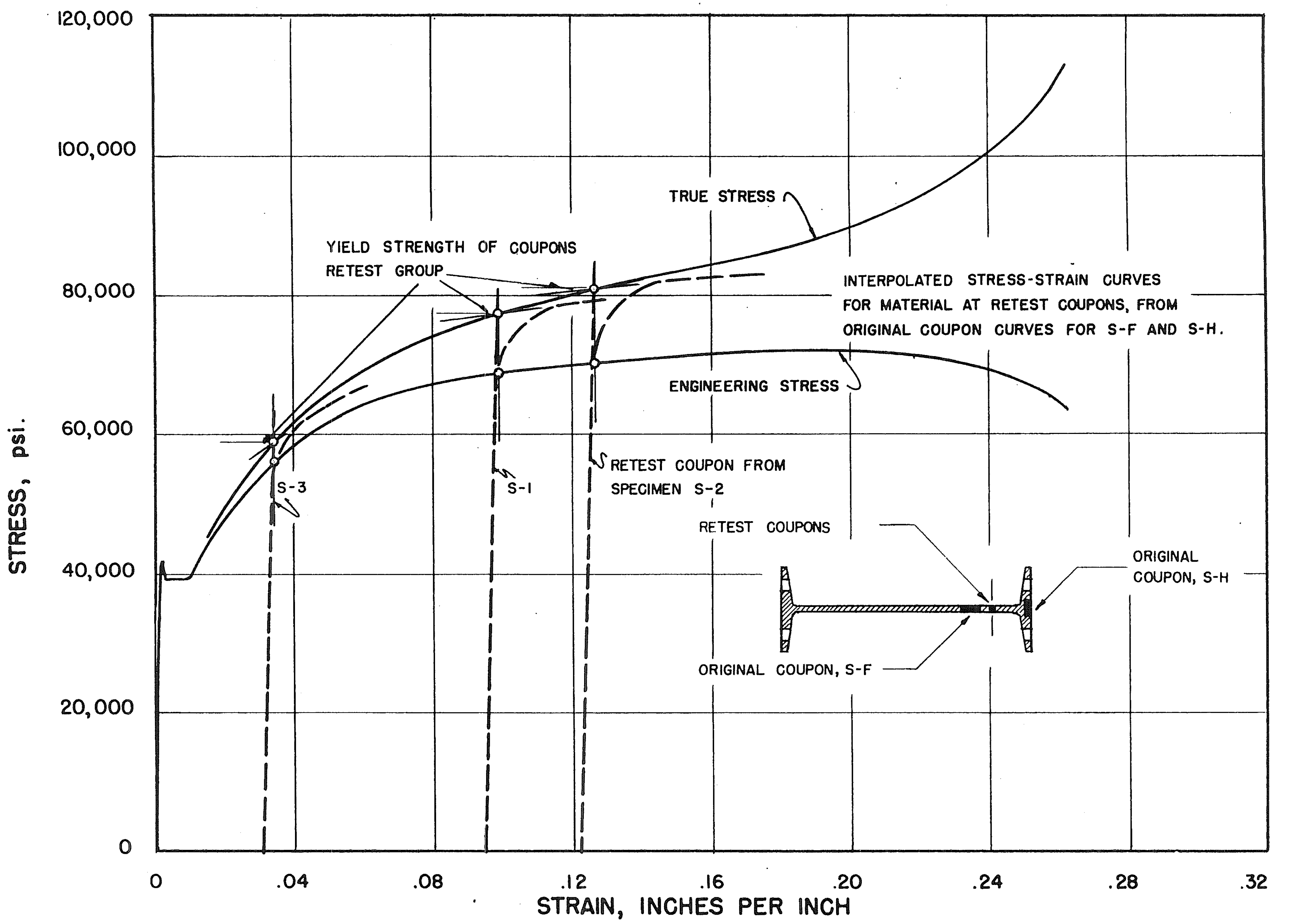


FIG. 34 TYPICAL STRESS-STRAIN DIAGRAMS

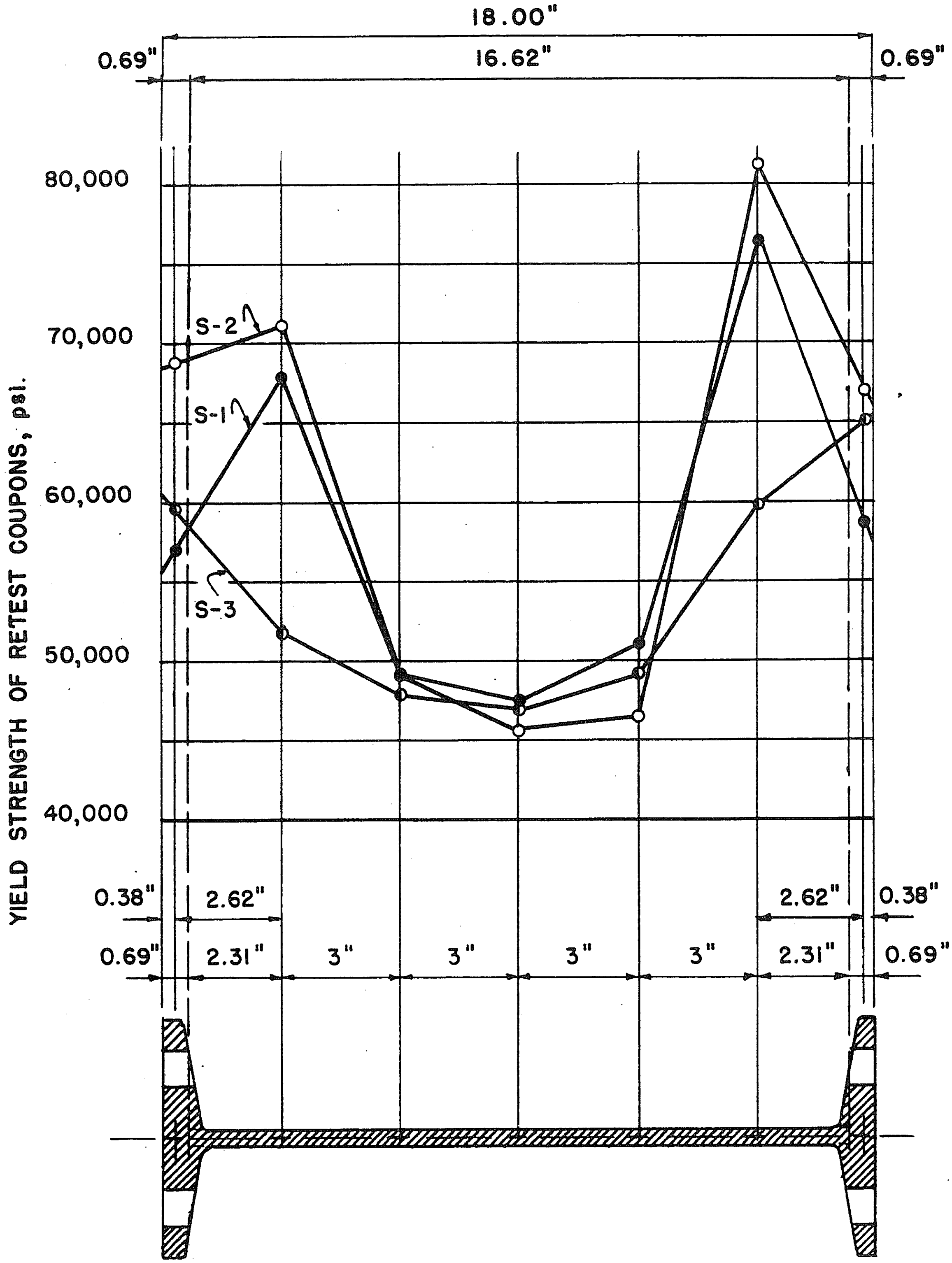


FIG. 35 YIELD STRENGTH DISTRIBUTION DIAGRAMS FOR RETEST COUPONS FROM SPECIMENS S-1, S-2 AND S-3.

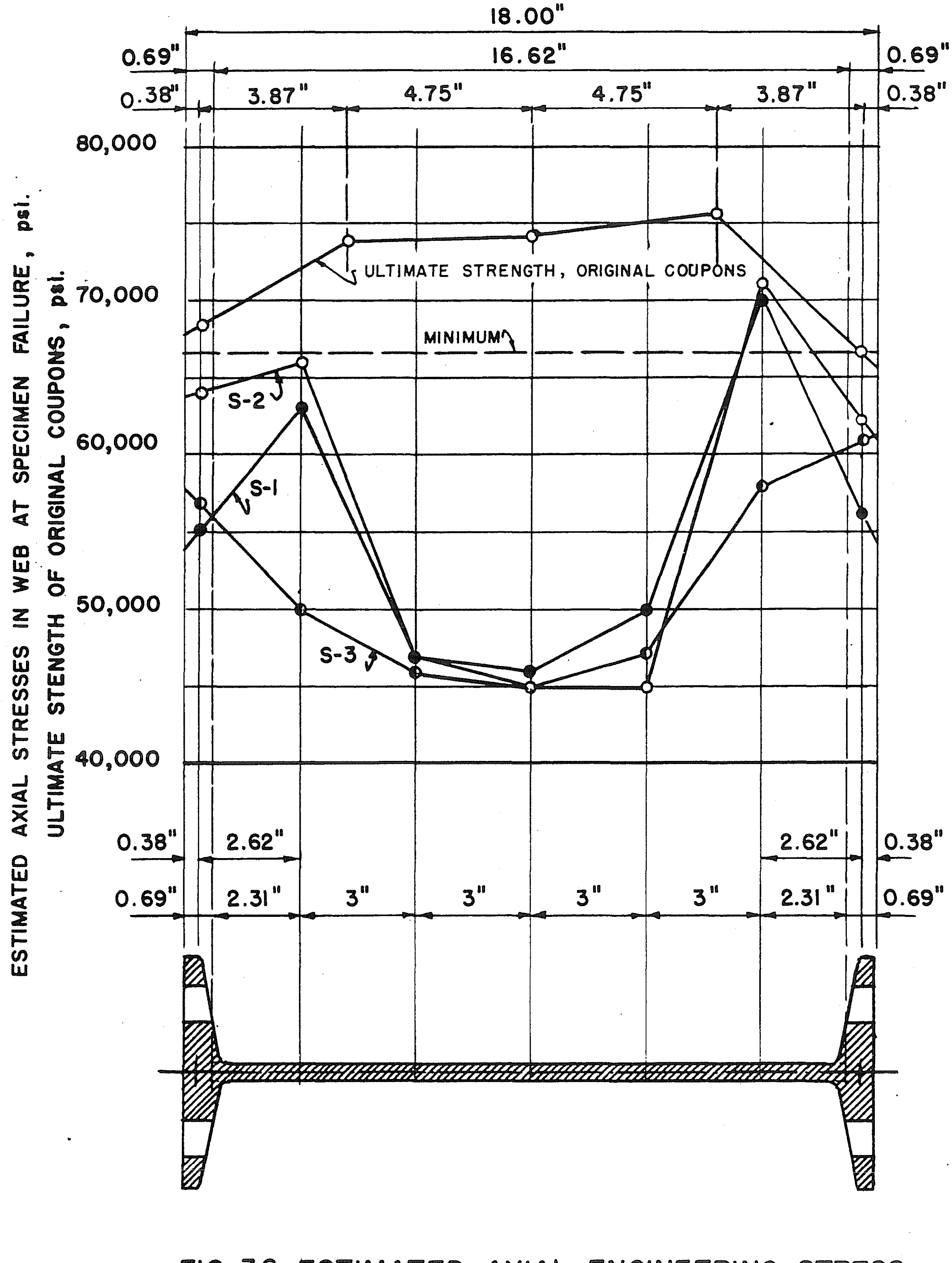


FIG. 36 ESTIMATED AXIAL ENGINEERING STRESS DISTRIBUTION IN WEBS OF SPECIMEN S-1, S-2 AND S-3 AT FAILURE.